Geology, Earthquake Hazards, and Land Use in the Helena Area, Montana—A Review

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By ROBERT GEORGE SCHMIDT

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A review of the earthquake problem at and near the capital of Montana—a first step toward the reduction of earthquake hazards in this rapidly developing region

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By Robert George Schmidt[1]

ABSTRACT

The Helena area covers about 1,036 km^2 of the northern Rocky Mountains in west-central Montana and encompasses the Helena and East Helena 15-minute topographic quadrangles of the U.S. Geological Survey. Most of the area is in Lewis and Clark County. A portion at the south is in Jefferson and Broadwater Counties. The large, sediment-filled basin called Helena Valley, about 415 km^2 in extent, is the principal physiographic feature in the area. Broad slopes at the edge of this valley rise gradually toward and butt sharply against surrounding mountains. Helena, the State capital, lies at the southwest border of the valley; the Missouri River is at the northeast margin. Lake Helena in the northern part of the valley, Helena Valley Regulating Reservoir in the eastern part, and Hauser Lake on the Missouri River are the main bodies of surface water in the area. Drainage in the area is to the Missouri, chiefly through Helena Valley.

Two main types of earth materials are present in the area: surficial deposits and bedrock. The surficial deposits, which mainly occupy the lowlands, include artificial fill, placer tailings, landslide deposits, stream deposits, slope wash, wind-laid deposits, glacial-lake deposits, and older gravel of Quaternary age and older stream and lake deposits of Tertiary age. In general, these materials consist of uncemented to weakly cemented gravel, sand, silt, and clay. Bedrock, which forms the mountains and hills and the substrate beneath the surficial deposits, is subdivided into sedimentary rocks of Cretaceous to Middle Proterozoic age, plutonic rocks of Tertiary and Cretaceous age, and volcanic rocks of Cretaceous age. Most of the bedrock is hard, firm, and permanently and strongly cohesive.

Faults are numerous in the area. They are mainly located in and adjacent to a linear zone of crustal discontinuity known as the Lewis and Clark line, which extends northwestward through the area and encompasses most of Helena Valley. Several faults within the Lewis and Clark line are categorized as potentially active fractures. They are the Bald Butte fault, a strike-slip fracture at the southern boundary of the line; the Helena Valley fault, a strike-slip fracture at the northern boundary; and the Scratchgravel Hills, Spokane Bench, Regulating Reservoir, and Spokane Hills normal faults, which are smaller cross-fractures within the line.

Most earthquakes are caused by sudden slippage along faults beneath the Earth's surface. The sudden rupture of a fault releases elastic energy stored in the adjacent rocks and produces seismic waves that travel rapidly through the Earth and excite its surface into vibrational motion. The focus or hypocenter of an earthquake is the point in the Earth's crust where fault rupture begins; the epicenter is the point on the Earth's surface directly above the focus. Magnitude, which is a rough measure of the size of an earthquake, is based on seismograph readings. Earthquakes of magnitude greater than about 5.0 may be destructive. The intensity of an earthquake is a measure of its local severity as determined by its effect on people, manmade structures, and the ground surface. On the Modified Mercalli Intensity Scale of 1931, which is widely used in the United States, earthquakes range from I to XII in order of increasing severity.

Several hundred earthquakes have been felt in the Helena region since it was first settled in 1864. Most of these shocks have been of weak to moderate Mercalli intensity (II-IV), but, in 1935, a destructive earthquake of intensity VIII caused extensive damage. The main shock of that earthquake was of magnitude 6¼. In a recent study of seismicity in the area, Freidline, Smith, and Blackwell (1976) recorded 97 small earthquakes from June 25 to August 18, 1973. About half of the epicenters of these earthquakes cluster along the trace of the Bald Butte fault and suggest that it may be the locus of much of the current seismic activity in the area. Seismic activity at an intensity of I-V is almost certain to continue in the future, and the possibility exists that a damaging earthquake of intensity VI or greater might occur at any time. The area is in the highest risk zone (zone 3) on the seismic zonation map in the Uniform Building Code.

Ground shaking is in most instances the chief hazard associated with earthquakes. Its severity largely depends upon earthquake magnitude and size of fault rupture and upon distance from the earthquake source. It also may be greatly influenced by the distribution of surficial deposits and bedrock at the earthquake site. In many earthquakes, the intensity of ground shaking has been reported to be greater on unconsolidated surficial deposits than on nearby bedrock. Damage from ground shaking is mainly caused by the horizontal component of movement and is closely dependent upon dynamic characteristics of the motion such as acceleration, velocity, displacement, duration, and frequency content.

Secondary effects that involve sudden failure of the ground and movement of water surfaces commonly accompany strong earthquakes. These hazards, which can be highly destructive, include landsliding, liquefaction-induced failure, surface faulting, regional land displacement, settlement, ground cracking, ridging and furrowing, ground churning, and seiches (standing waves) and wave surges in surface waters. The severity of these effects generally correlates with the intensity and duration of ground shaking and with the prevalence of geologic, topographic, and hydrologic conditions at the earthquake site that can enhance these hazards.

The surficial deposits in the area are capable of amplifying earthquake ground motion in future strong earthquakes. Enhanced shaking on these materials was probably a major cause of widespread damage in Helena during the earthquake of 1935. Data presented in the report suggest that the intensity of ground shaking generally can be expected to be least on bedrock; slightly greater on the bulk of the older stream and lake deposits; intermediate on stream deposits, slope wash, wind-laid deposits, glacial-

[1]Deceased, 1983. Information in this report is current to 1979; later illness prevented the author from continuing his investigations. Subsequent State and Federally funded research is refining information contained herein, and is applying observations and conclusions to land-use planning and earthquake-hazard mitigation in the Helena, Mont., area.

lake deposits, older gravel, and older bentonitic clays; and greatest on artificial fill, placer tailings, and landslide deposits. The data further indicate that the intensity of shaking may increase substantially on surficial deposits where the water table is close to the ground surface.

The susceptibility of surficial deposits to ground failure contributes to the potential seismic hazard in the area. Surficial materials prone to landsliding are present on hill and valley slopes; in streambank, lakeshore, and terrace and bench scarps; and in steep-sided manmade embankments and excavations. Old landslide deposits also may undergo renewed movements during earthquakes, but, in the Helena area, these features are far from urban centers. Liquefaction effects are likely to occur in water-saturated sediments in the lower part of Helena Valley and along the shores of Hauser Lake. Flood plains, irrigation-canal embankments, and earth dams also may include silt and sand that are susceptible to liquefaction. Artificial fill and placer tailings have the greatest potential for settlement and cracking in future strong earthquakes, but these modes of failure also may occur on the broad expanse of stream deposits in the western part of Helena Valley and on flood plains.

Steep bedrock slopes in the mountains and in escarpments along the Missouri River are potential sites of landsliding during future strong earthquakes. The flanks of Mount Ascension and Mount Helena, the slopes at the eastern front of the Scratchgravel Hills, and the declivities along the upper parts of Last Chance Gulch, Dry Gulch, and Tenmile Creek pose the chief threat to urbanized areas.

Faults in the area that are potentially active constitute a seismic hazard. The Bald Butte and Helena Valley faults are probably capable of generating destructive earthquakes and have a high potential for surface rupture. The Scratchgravel Hills, Spokane Bench, and Spokane Hills faults also may have the capacity to produce damaging earthquakes and may be susceptible to reactivation and to surface breakage. Other faults in the area are a lesser hazard. The Helena Valley, Spokane Bench, and Spokane Hills faults have the potential to produce regional ground displacement that might affect surface waters.

Hauser Lake on the Missouri River, Lake Helena, and the Helena Valley Regulating Reservoir are the principal bodies of surface water in the area on which earthquake-generated seiches or surges might form and flood the shoreline. The narrow portions of Hauser Lake, which would tend to constrict water oscillation, might sustain the greatest wave heights from earthquake-induced waves.

Protection from earthquakes largely rests upon the engineering practice of making structures earthquake resistive. Land use is a supplemental means for seismic protection. It involves the siting of vulnerable structures and concentrations of people away from the places where the potential danger from earthquake hazards is greatest.

The principal lands in the area on which it may be necessary to restrict structural development to achieve adequate seismic protection include: (1) land that has a high potential for intensified shaking and ground failure—chiefly land underlain by thick artificial fill and placer tailings and land underlain by surficial deposits in which the water table is at shallow depth; (2) steep slopes on surficial deposits and on bedrock that are prone to landsliding; (3) land along the trace of potentially active faults on which there is a risk of surface rupture; and (4) shoreline land susceptible to flooding from earthquake-induced water waves.

Land underlain by stream deposits, slope wash, wind-laid deposits, glacial-lake deposits, older gravel, and older bentonitic clays, on which the water table is relatively deep (10 m or more) and on which landslide, fault, and flood hazards are minimal, is of intermediate seismic risk to structures. On this ground, adequate protection from earthquakes probably can be attained by a suitable combination of structural design requirements and land use.

Bedrock terrain and, to a somewhat lesser degree, land underlain by older stream and lake deposits (apart from older bentonitic clays), in areas not subject to landslide, fault, or flood hazards, generally present the lowest seismic risk to structures. From a seismic viewpoint, these lands are most suited for high-density structural development.

The ideal objective in earthquake hazards assessment is to quantitatively define the level of earthquake effects that can be expected in any area during future earthquakes of specific magnitude and location. The presentation of this information in map form is known as "seismic microzonation."

The information in this report is not sufficiently accurate to estimate earthquake effects with the precision required for comprehensive seismic zoning and engineering application. Additional quantitative data are needed on seismicity, on behavior of surficial deposits under conditions of earthquake loading, on physical characteristics of potentially active faults, on liquefaction potential, on slope stability, and on flood potential to formulate rational land-use and engineering policies that will effectively minimize seismic hazards in the area.

An effective program to reduce earthquake hazards requires a major, long-term effort that enlists the expertise of many individuals from a variety of professions. The responsibility for formulating and implementing a program of earthquake hazards reduction in Montana will largely rest with the State Earthquake Hazard Mitigation Committee. Much of the research required for earthquake hazards assessment under the aegis of the committee could be accomplished by State and local agencies, colleges, and universities.

INTRODUCTION

Earthquakes, which cause some of the greatest natural disasters on Earth, are a serious problem in highly seismic regions of the United States, and elsewhere in the world; and concern about them has become more urgent as population increases and cities continue to grow. Accordingly, public officials and people concerned with land development in these regions have become increasingly attentive to the possible effects of future destructive earthquakes and to the ways in which damage and loss of life from them may be minimized. It is therefore prudent that knowledge about earthquakes and their potential hazards be widely publicized.

The effect that an earthquake may have in an area depends to a large extent on the local geologic conditions at the earthquake site. Consequently, basic geologic data are essential to realistically assess seismic hazards and to establish broad land-use practices that will help reduce future earthquake losses. This report treats the earthquake problem in the Helena area from that standpoint. It describes the local geology, potential earthquake hazards, and local geologic conditions that may contribute to seismic hazards and briefly outlines the implications these factors have for land use and for earthquake protection. A brief account of the nature of earthquakes and a short summary of the seismic history of the area are included in the discussion. The future assessment of seismic hazards in the area, emphasizing the need for quantitative earth-science data, is examined in a concluding section of the report. The report is general in scope and nontechnical in approach. It is conceived as a useful first step toward the reduction of earthquake hazards in the Helena area.

LOCATION

The Helena area is in the northern Rocky Mountains in west-central Montana and, for the purpose of this report, is considered as the area encompassed by the Helena and East Helena 15-minute topographic quadrangles of the U.S. Geological Survey (fig. 1). These quadrangles lie between long 111°45′ W. and 112°15′ W. and lat 46°30′ N. and 46°45′ N. and have a combined area of about 1,036 km^2. Most of the area is in Lewis and Clark County. About 207 km^2 at the south is in Jefferson and Broadwater Counties. Helena, the State capital, which has a population of about 25,000, is in the south-central part of the area. The Missouri River flows across the northeastern part.

PREVIOUS STUDIES

Several earlier studies have focused upon the geology and earthquake activity of the Helena area. Knopf (1913) described the ore deposits in the region and provided information on regional geology. Pardee and Shrader (1933) also furnished data on metalliferous deposits and observed salient features of the geology, and Pardee (1950) discussed block faulting in the area. The ground-water resources of Helena Valley were studied by Lorenz and Swenson (1951). A geologic map of the southern and western parts of the area was compiled by Knopf (1963), and the geology of the southeastern part was mapped by Smedes (1966, pl. 1) in a study of the northern Elkhorn Mountains. Davis and others (1963) interpreted the subsurface geologic structure in the eastern part of the area from gravity and aeromagnetic data. Most reports on earthquake activity have dealt with the destructive earthquake that occurred at Helena in 1935; seismic data, geologic phenomena, and damage resulting from that quake were documented by Engle (1936), Scott (1936), Ulrich (1936), and Neumann (1937). Most recently, the results of an earthquake survey conducted in the Helena area in 1973 were described by Freidline and others (1976).

FIELDWORK AND ACKNOWLEDGMENTS

Most of the geologic information in this report was acquired during field studies in the summers of 1975, 1976, and 1977. The author was ably assisted in that work by William R. Trojan in 1975, D. Guy Waggoner in 1976, and Richard Hazelwood in 1977. Photographs of some of the damage sustained in the Helena earthquake of 1935 were provided by Sidney L. Groff of the Montana Bureau of Mines and Geology. Several colleagues on the staff of the U.S. Geological Survey have contributed ideas and information that have been helpful to the study: S. Warren Hobbs and William B. Joyner critically read an early draft of the report; Mitchell W. Reynolds provided unpublished data on the Helena Valley, Spokane Bench, Regulating Reservoir, and Spokane Hills faults in the East Helena quadrangle; and A. Frank Bateman, Jr. furnished information on a unique structural failure that occurred at the Kessler Brewery in Helena during the 1935 earthquake.

GEOLOGY

PHYSIOGRAPHY AND DRAINAGE

The principal physiographic feature in the area is the broad, northwest-trending, oval-shaped basin called Helena or Prickly Pear Valley. This valley, which is largely ringed by mountains, is about 32 km long and as much as 19 km wide. Its area is about 415 km^2. The lowest part of the valley is occupied by Lake Helena, which is formed by back-up from Hauser Dam on the Missouri River. The lake covers an area of about 8 km^2 and has a surface elevation of about 1,113 m. The western part of the valley, which contains Lake Helena, is gently sloping and has a broad, flat floor. It is largely surfaced by young stream deposits and slope wash. The eastern part of the valley, which is higher, comprises low rolling hills and flat-topped benches. It is mainly underlain by older stream and lake deposits. The sides of the valley are marked by broad, gently inclined slopes that butt sharply against the surrounding mountains at elevations of about 1,160-1,280 m.

At the south and southwest, Helena Valley is bordered by steep, rugged mountains that extend westward to the Continental Divide some 20 km away. The city of Helena is situated on the southern slope of the valley where it abuts this mountain front. Mount Helena and Mount Ascension, with altitudes, respectively, of about 1,664 and 1,632 m, rise abruptly above the southern margins of the city. On the west, the valley is bounded by the Scratchgravel Hills, which extend northward about 7 km and attain an elevation of about 1,601 m. They are connected on the west to the main range of the Rocky Mountains by a broad low ridge. The northern boundary of the valley is formed by a group of low hills whose summits are at altitudes of about 1,433-1,585 m. Over a short stretch on the northeast, the valley is bordered by Hauser Lake, on the Missouri River, beyond which are the Big Belt Mountains that attain a height of more than 2,400 m. The southeastern part of the valley is sandwiched between the Spokane Hills on the east and the

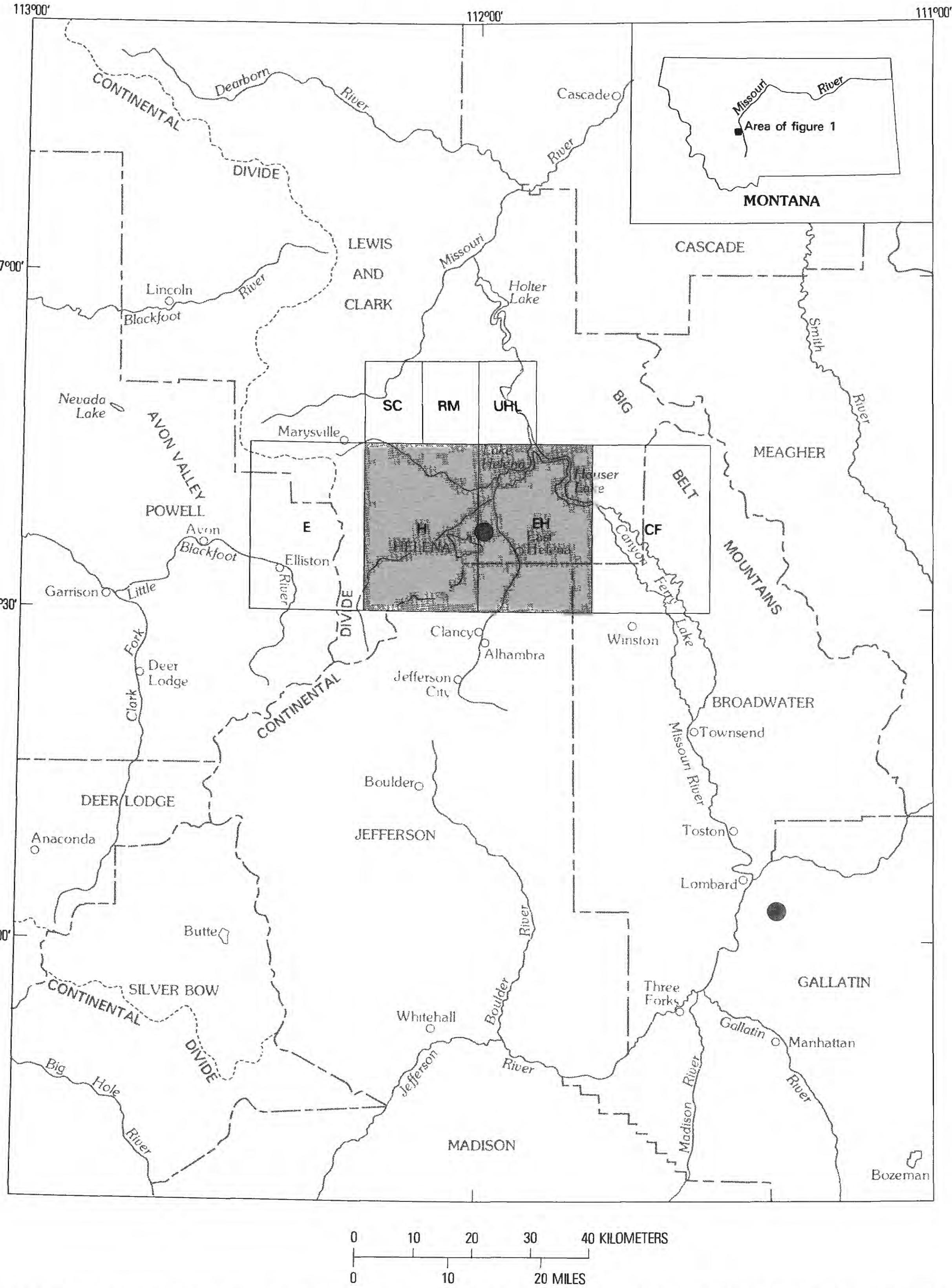


FIGURE 1.—Map showing location of Helena area (shaded) and location of U.S. Geological Survey quadrangles mentioned in this report. SC, Silver City quadrangle; RM, Rattlesnake Mountain quadrangle; UHL, Upper Holter Lake quadrangle; E, Elliston quadrangle; H, Helena quadrangle; EH, East Helena quadrangle; CF, Canyon Ferry quadrangle. Circles mark epicenters of the Lombard earthquake of 1925 and the main shock of the Helena earthquake of 1935.

steep northern flank of the Elkhorn Mountains on the south. A low divide between these ranges separates Helena Valley from Townsend valley. The Spokane Hills reach an altitude of about 1,682 m. The Elkhorn Mountains are high and rugged; far south of Helena Valley they culminate in Elkhorn and Crow Peaks at elevations above 2,740 m.

Much of the area is drained by a network of perennial streams that lead into Helena Valley from the mountains to the south and west. The valley, in turn, is drained by the Missouri River, chiefly through Lake Helena. The principal streams that enter the valley are Spokane Creek, Prickly Pear Creek, Tenmile Creek, Sevenmile Creek, and Silver Creek. Spokane Creek, which drains the mountains to the southeast, flows northward along the southeastern margin of the valley and empties into Hauser Lake on the Missouri River. Prickly Pear Creek, which drains a large area of mountains to the south, divides into several distributaries on entering the valley near East Helena. Its main branch flows northwestward across the valley to Lake Helena. Tenmile Creek, which drains the mountains to the southwest, enters the valley a short distance west of Helena and flows northeastward to join Prickly Pear Creek about 1½ km southwest of Lake Helena. Sevenmile Creek drains the mountains to the west, flows eastward into the valley south of the Scratchgravel Hills, and joins Tenmile Creek about 5 km north of Helena. Silver Creek runs southeastward through the northwestern part of the area and, on entering the valley north of the Scratchgravel Hills, flows eastward to Lake Helena.

The mountains immediately south of Helena are mostly drained by north-flowing, intermittent streams that lead into Helena Valley through Orofino Gulch, Grizzly Gulch, Last Chance Gulch, and Dry Gulch. The flow of these streams is ordinarily absorbed by the streambeds before it reaches the valley. Last Chance Gulch, which runs through the center of Helena, is formed by the mergence of Orofino and Grizzly Gulches a short distance south of the city. Dry Gulch issues from the mountains along upper Davis Street in the eastern part of Helena. The mountains north of Helena Valley are drained by small intermittent streams that empty into the valley or into the Missouri River. The mountains in the northeastern part of the area, on the east side of the Missouri River, are part of the Big Belt Range; they are largely drained by perennial streams that flow into the Missouri. The principal streams there are Trout Creek and Soup Creek.

An elaborate system of canals and ditches extends around and across the central part of Helena Valley to supply water for irrigating crops. The irrigation water is mainly derived from Lake Helena and the Missouri River, and supplemental water is obtained from Prickly Pear, Tenmile, Sevenmile, and Silver Creeks. Water from the Missouri is pumped upward from a point just below Canyon Ferry Dam in the Canyon Ferry quadrangle to a tunnel that leads through the Spokane Hills and is impounded in a large regulating reservoir in the eastern part of the valley before it enters the main irrigation system. Altogether, about 130 km^2 of land in the valley is under irrigation.

About 36 km^2 of ground in the lower part of Helena Valley is periodically waterlogged due to the irrigation (Lorenz and Swenson, 1951, p. 39). This condition is caused by excessive ground-water recharge resulting from irrigation of higher lands in the valley. The irrigation water sinks into the ground and moves down along the water table toward the lower part of the valley. There the ground is unable to transmit the excess water, and so it is forced to the surface. The largest area of waterlogged land, covering about 33 km^2, lies south of Lake Helena and extends up the main course of Prickly Pear Creek beyond Lake Stanchfield; a smaller area of waterlogged ground, covering about 3 km^2, lies at the confluence of Tenmile and Sevenmile Creeks. These areas are essentially bounded by the 6 ft (1.8 m) water-table line shown on plates 1 and 2. The water issues over a fairly continuous surface in the waterlogged areas, and the land is marshy, swampy, spongy, and highly unstable. Several years ago, in an attempt to reclaim the waterlogged ground, drainage canals were dug to carry the excess water to Lake Helena and to Prickly Pear, Tenmile, and Sevenmile Creeks. This operation met with little success, however, for though the water table was lowered to normal levels near the canals it remained excessively high in the areas between them (K.R. Wilke, oral commun., 1977).

ROCKS

In a geological sense, the term rock signifies any naturally formed aggregate or mass of mineral matter that constitutes part of the Earth's crust. Therefore, in the broadest sense, rocks include not only the hard, firmly consolidated materials of the Earth's surface but also the soft, unconsolidated and weakly consolidated sediments such as clay, silt, sand, and gravel. In general, the firmly consolidated materials are categorized as bedrock, and the unconsolidated and weakly consolidated sediments are categorized as surficial deposits. In an engineering sense, the term rock is generally applied to firm, solid bedrock that cannot be excavated by normal methods alone, and surficial deposits and other soft earth materials are considered as soils.

Surficial deposits and bedrock are widespread in the Helena area. The surficial materials, which comprise a cover of uncemented and weakly cemented sediments on the bedrock, mainly occupy the lowlands. Bedrock forms the mountains and hills as well as the substrate beneath the surficial deposits. A rather detailed subdivision of the surficial deposits in the Helena area is presented in this study because ground motion and ground failure generated by earthquakes can vary significantly in different types of surficial materials.

SURFICIAL DEPOSITS

The surficial deposits are subdivided into nine units on the basis of differing physical characteristics and origin. These units include artificial fill, placer tailings, landslide deposits, stream deposits, slope wash, wind-laid deposits, glacial-lake deposits, and older gravel of Quaternary age (0–2 million years ago), and older stream and lake deposits of middle and late Tertiary age (2–38 million years ago). Some rocks in the older stream and lake deposits unit are hard and compact and could be classified as bedrock, but, because the bulk of the unit is composed of rocks that resemble the more orthodox surficial deposits, it is placed in the surficial category.

The areal distribution of the surficial units is shown on the accompanying maps of the Helena and East Helena quadrangles (pls. 1, 2). The deposits cover an aggregate area of about 410 km^2. The boundaries of the units on the ground surface are covered in most places with soil and vegetation and their location generally must be inferred. The position of the boundaries shown on the maps is therefore approximate. Stream deposits and slope wash are combined as a single unit in areas where it is impractical to separate them because of poor exposure or because of the map scale.

The distribution and physical characteristics of the surficial deposits are important factors in evaluating seismic hazards in the Helena area. Data from many parts of the world show that damage to manmade structures during earthquakes, and thus, presumably, the intensity of ground motion, is commonly greater on thick, soft sediments than on hard bedrock. Damage caused by the Helena earthquake of 1935 appears to have followed that pattern (Scott, 1936, p. 10). This aspect of the earthquake problem, as it relates to the Helena area, is examined more fully in the section on "Local geologic conditions that may contribute to seismic hazards."

The descriptions of the surficial units that follow are based largely on visual inspection of the rocks in natural outcrops and are of a general nature. A few observations concerning the mechanical stability of the deposits are included in the descriptions; specific engineering properties of the materials are unknown.

ARTIFICIAL FILL

The unit mapped as artificial fill (pls. 1, 2) includes a mass of earth fill along Last Chance Gulch between Neill Avenue and the Burlington-Northern Railway tracks in the city of Helena, the old city trash dump northeast of Helena, and slag piles at the American Smelting and Refining Company smelter in East Helena. The aggregate area covered by these deposits is about 24 ha (60 acres). Other bodies of artificial fill, not shown on the maps, include road and airport-runway foundations, earth dams at reservoir sites, irrigation-canal and railway embankments, pads of supportive gravel beneath some of the newer building and parking lots, and small masses of earth fill around manmade structures. The earth fill along Last Chance Gulch is as much as 4 m thick, the trash-dump fill is as much as 3 m thick, and the slag piles at East Helena are as much as 15 m thick. The other masses of artificial fill are mostly less than 2 m thick, but earth fill in some of the road approaches to Interstate Highway 15 is as much as 4 or 5 m thick.

The earth fill along Last Chance Gulch and around manmade structures consists mostly of mixed soil and rock derived from local excavations. This material is coarse to fine grained, unsorted, unstratified, and loosely to moderately compacted. The earth fill in road and airport-runway foundations, on the other hand, is largely rounded gravel that was mined from local pits and screened to various sizes. This material, which has coarser material at the base and finer at the top, is crudely stratified and firmly compacted. The pads of supportive gravel fill beneath buildings and parking lots also are mostly well sorted, rounded gravel. However, this material is unstratified and is probably not as thoroughly compacted as the road and runway fill. The refuse fill in the old city dump consists of a heterogeneous mixture of metal, glass, wood, paper, and animal and vegetable matter covered with a thin layer of earth. In general, it is loosely compacted, unstratified, and unsorted. The slag piles at the smelter in East Helena are formed of angular fragments of fused rock (clinker) resulting from the ore-smelting process. This material is generally well compacted and is quite firm due to the interlocking arrangement of the clinker fragments.

In general, artificial fill has a relatively low shearing resistance compared to natural surficial materials, especially when saturated with water, and it is prone to dislocation by settlement, cracking, and slumping when subjected to strong earthquake ground motion.

PLACER TAILINGS

This unit constitutes waste rock resulting from placer mining. The largest body of tailings, produced by dredging, covers an area of about 2 km^2 on the northern outskirts of Helena (pl. 1). Other large bodies of tailings, which together underlie an additional $1\frac{1}{2}$ km^2, are present along the upper part of Silver Creek (pl. 1); on Eldorado Bar, Gruel Bar, and Spokane Bar along the Missouri River (pl. 2); and along Holmes Gulch and Prickly Pear Creek south of East Helena (pl. 2). Smaller accumulations, not shown on the maps, are found along Sevenmile Creek above Birdseye (pl. 1), along Mitchell Gulch southeast of East Helena (pl. 2), and on McCune Bar and Danas Bar along the Missouri River (pl. 2). Much of the streambed of Last Chance Gulch that lies beneath the city of Helena also consists of placer tailings.

The placer tailings, which are derived from stream and terrace deposits, mainly consist of large piles of coarse, washed gravel, commonly arranged in long rows. The maximum height of the piles, and thus the thickness of the deposits, is about 5 m. In general, the gravel is unsorted, unstratified, and loosely compacted; it is composed of a mixture of boulders, cobbles, pebbles, and coarse sand. The chief rock constituents are quartzite, granite, volcanic rock (traprock), shale, and limestone. Some of the coarsest gravel is in the southern part of the tailings mass on the outskirts of Helena where a few boulders are as much as a meter across and many are as much as half a meter across. Because the placer tailings are extremely porous, water drains through them rapidly. In engineering terms, they probably can be classified as open-work gravel.

The loosely compacted tailings are prone to slumping and internal movement if disturbed. Mechanically, they probably form the most unstable rock unit in the Helena area, but, in spite of this, several large structures have been built upon them.

LANDSLIDE DEPOSITS

Landslide deposits are rare in the area and are far from urban centers. They have been recognized only at the head of Park Gulch in the northwestern part of the Helena quadrangle (pl. 1) and along the northern front of the Elkhorn Mountains in the southeastern part of the East Helena quadrangle (pl. 2). The deposits consist of thick masses of coarse, jumbled, dislocated rock debris that broke away from steep cliffs and moved downward as gravity-propelled earthflows. The material is unsorted, unstratified, loosely compacted, and extremely porous. The surface of the deposits is rough and hummocky and has small closed depressions. The landslide deposit at the head of Park Gulch extends a short way into the adjoining Elliston quadrangle. It has an area of about 1 km^2 and consists mainly of large blocks and smaller fragments of quartzite intermixed with soil. The landslide mass along the front of the Elkhorn Mountains covers about ½ km^2 and consists of broken fragments of volcanic breccia, lava, and lavalike tuff intermixed with soil and slope wash. The maximum thickness of each deposit is about 12 m.

A growth of tall trees on both of the landslides indicates that the deposits originated scores of years ago. Additionally, there is no evidence of recent movement, such as tilted trees, within or along the margins of the slides, which shows that they have been stabilized for many years. The material is, however, loosely compacted and prone to failure by landslip and settling if disturbed.

STREAM DEPOSITS

Stream deposits, the natural materials laid down in stream channels and on flood plains, occupy about 185 km^2 of the land surface in the area. Most of the western floor of Helena Valley, encompassing an area of about 150 km^2, is covered by these deposits, and they are widely distributed on the floors of the major stream valleys and dry gulches in the area (pls. 1, 2). The stream deposits in Helena Valley comprise sediments brought in chiefly by Prickly Pear, Tenmile, Sevenmile, and Silver Creeks over the past several hundred thousand years.

The stream deposits consist mainly of beds of rounded to subrounded pebble, cobble, and boulder gravel interlayered with thin beds and lenses of sand, silt, and clay. The matrix of the gravels ordinarily consists of coarse sand. The deposits are generally well sorted, stratified (layered), and uncemented. The material in existing stream channels is ordinarily loose and weakly compacted; older material on stream flood plains and beneath the land surface is generally well compacted. The rock constituents of the gravels, which have been derived largely from upstream sources in the surrounding mountains, are mainly quartzite, granite, volcanic rock (traprock), shale, and limestone. The sands are medium to coarse and consist chiefly of small grains of quartz, chert, feldspar, and magnetite, and tiny rock fragments. The silts are very fine grained and are composed of minute but visible grains of quartz and feldspar, flake-shaped particles of mica and chlorite, and small amounts of organic matter. The clays are mainly an aggregate of microscopic flakes of clay minerals. They are usually silty or sandy.

Beds of gravel in the stream deposits range from ½ m or less to as much as 3 m thick. Beds of sand, silt, and clay are generally much thinner and range from less than a few centimeters to perhaps 1 m thick. Because of the constantly changing position and velocity of individual stream courses during deposition, the deposits vary greatly from place to place in their sequential makeup and grain size. In general, the stream deposits in Helena Valley are coarser grained and thicker near the bordering mountains and are finer grained and thinner in the lower parts of the valley. A well drilled in the flood plain of Tenmile Creek at the Montana Club (now the Green Meadow Country Club) penetrated about 30 m of uncemented gravel and sand before entering older stream and lake deposits below (Lorenz and Swenson, 1951, p. 18). This thickness is probably about the maximum for the stream deposits in Helena Valley. Along the major streams away from the valley, the deposits probably have a maximum thickness of about 12 m; in smaller valleys the deposits are mostly less than 3 m thick.

Apart from loose, weakly compacted sediments in existing stream channels, the stream deposits are basically quite stable in an engineering sense. For example, steep to vertical walls in some gravel pits have stood for years without appreciable slumping. On the other hand, water-saturated sands and silts in the deposits below the water table are probably susceptible to loss of strength and to failure by internal movement if disturbed by strong earthquake ground motion. This relation is examined in further detail in the section on "Local geologic conditions that may contribute to seismic hazards."

SLOPE WASH

Slope wash comprises soil and rock material deposited on slopes by the action of gravity and by surface-water runoff not concentrated into channels. The material has been mapped only where it is of considerable extent and thickness. It is present chiefly on broad, gentle slopes along the southern, western, and northern margins of Helena Valley (pls. 1, 2). Altogether, about 50 km^2 in the area, including large parts of Helena and East Helena, all of the Helena Airport, and much of Fort Harrison, is underlain by these deposits. The slope wash was shed from bedrock outcrops on the steep slopes that rise above the deposits, and it thickens downslope away from the bedrock source. Its thickness ranges from a feather edge at the headward margins to a maximum of perhaps 6 m at lower elevations.

The slope wash consists of beds of coarse gravel interlayered with thin irregular beds and lenses of silt and clay. The gravel is composed of angular to subrounded fragments of bedrock in a matrix of sandy and silty clay whose volume usually exceeds that of the fragments. Along the southern margin of Helena Valley, the gravel fragments are chiefly quartzite, shale, and limestone; on the southern and eastern slopes of the Scratchgravel Hills, mainly granite and shale; along the northern margin of the valley, mainly shale; and along the northern flank of the Elkhorn Mountains, in the southeastern part of the valley, mostly lava and lavalike volcanic tuff (traprock). Where the deposits are extensive, as along the southern and northern margins of Helena Valley, the gravel becomes progressively finer downslope. Near the bordering mountains it commonly contains blocks as much as half a meter across; at lower elevations the gravel fragments are mainly of pebble size. In general, the slope wash is composed of an uneven assortment of rock fragments, is poorly stratified, and is firmly compacted. It contains a large proportion of clay but little sand, and the majority of its contained rock fragments are angular. These features serve to distinguish the material from adjoining stream deposits.

Most of the slope wash lies on inclined surfaces above stream levels and is well drained; the deeper parts of thick accumulations in the distal portions of some deposits may be saturated with water. In general, the material is thoroughly compacted and appears to be quite stable mechanically, for slumping and subsidence of the deposits were not observed.

WIND-LAID DEPOSITS

Wind-laid deposits include dunelike accumulations of sand and silt on lowland areas along the Missouri River and blanketing deposits of silt on upland surfaces in the Spokane Hills (pl. 2). The aggregate area covered by the deposits is about 10 km^2.

The wind-laid deposits along the Missouri River are found chiefly at the base of hillslopes at the inner margins of terrace surfaces at Eldorado Bar, McCune Bar, Danas Bar, Spokane Bar, and Gruel Bar. This material was mainly derived as wind-blown sediment from terrace gravel and glacial-lake sediments that underlie the terraces, and it consists largely of fine, well-sorted sand made up of rounded grains of quartz and feldspar. The sand is unstratified, loosely to firmly compacted, and highly porous. Some of the wind-laid deposits along the Missouri contain large amounts of silt and clay and are much firmer than the well-sorted sands. A large area along York Road in the vicinity of Lakeside School, on the west side of Hauser Lake, is underlain by this material. The maximum thickness of the wind-laid deposits along the Missouri River is about 6 m.

Deposits of silt are widely distributed on bench surfaces along the north and west sides of the Spokane Hills in the southeastern part of the East Helena quadrangle (pl. 2) and also within the hills beyond (east of) the crest of the range in the adjoining Canyon Ferry quadrangle. In most places the silt is only a meter or so thick, but locally, where it has accumulated in ravines and depressions, it is as much as 5 m thick. It is well sorted, unstratified, and firmly compacted, and it stands in vertical walls as much as 5 m high. The silt, which consists of minute angular grains of quartz, feldspar, calcite, and mica in a binder of clay minerals, is commonly traversed by small, closely spaced, nearly vertical rootholes lined with organic matter. In all aspects, the material is similar to the type of deposit called loess, which is of wind-laid origin. Distribution of the silt suggests that northwesterly winds swept the material off the floor of Helena Valley and deposited it on the windward and leeward sides of the obstructing crest of the Spokane Hills.

In general, the wind-laid deposits are mechanically stable, although easily erodable. Because they generally lie on high ground above the water table, they are well drained. Where saturated with water, however, these deposits lose shearing resistance and become susceptible to failure by slumping, subsidence, and internal movement. Strong earthquake ground shaking tends to transform water-saturated sediments of this type into an essentially fluid state.

GLACIAL-LAKE DEPOSITS

Small patches of glacial-lake deposits are present on either side of Hauser Lake on the Missouri River, on the northeast shore of Lake Helena, and near the mouth of Spokane Creek (pl. 2). These materials were laid down in glacial lake Great Falls, which formed when the Missouri River was dammed by a continental ice sheet east of Great Falls, Montana, 20-30 thousand years ago. The deposits cover an area of about 3 km^2; their maximum thickness is about 12 m.

The glacial-lake deposits consist of sand, silt, and clay in beds a few millimeters to as much as 30 cm thick. In places the deposits are composed almost entirely of silt and clay in thin, alternating dark- and light-brown laminae 2-8 cm thick. Each pair of light and dark laminae is called a "glacial varve." Commonly the varved deposits contain small oblate and tubular calcareous concretions. Locally, layers of fine-grained, well-sorted, weakly cemented sand form the bulk of the deposits. The sands are composed chiefly of subrounded grains of quartz and chert and less abundant grains of feldspar and mica.

The glacial-lake deposits are firmly compacted. However, beds of sand and silt in the deposits are permeable, and the unit is highly unstable where saturated with water. For example, large-scale slumping of the deposits occurred along the shores of Hauser Lake as the waters rose behind Hauser Dam and submerged portions of these deposits. Strong earthquake ground motion would tend to reduce the shearing resistance of the water-saturated glacial-lake sediments and promote failure by slumping and subsidence.

OLDER GRAVEL

Older gravel lies on terrace surfaces along the major streams and in scattered patches along the southern and northern slopes of Helena Valley (pls. 1, 2). A few small masses of older gravel are present east of the Missouri River in the Big Belt Mountains (pl. 2), and the material covers an extensive area in the central part of Helena (pl. 1). The largest body of older gravel lies along the northern front of the Elkhorn Mountains in the East Helena quadrangle (pl. 2). Altogether, the older gravel covers an area of about 50 km^2. The maximum thickness of the deposits is about 20 m.

The older gravel constitutes ancient flood-plain and alluvial-fan deposits that were laid down many thousands of years ago when the streams were at higher levels. The material is coarse, moderately well sorted, and irregularly stratified. It is made up largely of rounded pebbles, cobbles, and boulders of granite, lava, welded tuff, quartzite, shale, and limestone in a matrix of coarse sand. Boulders as much as 1½ m across are present in the gravels; the bulk of the material, however, consists of pebbles and cobbles less than 10 cm across. Thin lenses of sand, silt, and clay are locally present in the deposits. The sands consist mainly of grains of quartz, chert, chalcedony, feldspar, magnetite, and fine-grained volcanic rock. The older gravels on terraces along the Missouri River and Silver Creek were in places extensively mined for gold by placer methods. The larger areas of mined gravel are shown as placer tailings on plates 1 and 2. Most of the older gravel is well compacted. In places it is firmly cemented with calcium carbonate (caliche) and in other places with red iron oxide, especially at the base.

The natural gravels are mechanically very stable and are subject to slumping only along the steep, stream-facing margins of terraces or where disturbed by placer mining. Most of the gravel is above the water table and is well drained.

OLDER STREAM AND LAKE DEPOSITS

Older stream and lake deposits are exposed over an area of about 120 km^2 in the eastern part of Helena Valley (pl. 2). In the western part of the valley, these units are largely covered by younger stream deposits and slope wash, but their presence is known from small exposures in the city of Helena (pl. 1) and from cuttings in deep water wells drilled at the Green Meadow Country Club, Fort Harrison, the Masonic Home, and the Montana State Vocational School. These occurrences suggest that the deposits are distributed over the entire western part of the valley at shallow depth. The northern two-thirds of Helena is probably underlain by older stream and lake deposits beneath a thin cover of younger surficial material.

The older stream and lake deposits presumably increase in thickness toward the central part of Helena Valley, but their maximum thickness is unknown. Knopf (1913, p. 94) reported a thickness of more than 365 m on the basis of wells drilled for artesian water, but he did not give the location of the holes. On the basis of a gravity survey conducted in the eastern part of the valley, Davis and others (1963, text, p. 3) concluded that the older stream and lake sediments in the vicinity of Lake Helena are more than 1,800 m thick. However, that thickness is unconfirmed. East and southeast of Lake Helena, about 400 m of older, south-dipping beds at the base of the sequence are overlain by roughly 100 m of younger, flat-lying material.

The older stream and lake deposits consist mainly of beds of clay, silt, sand, gravel, and volcanic ash that range in color from white through shades of gray, green, yellow, tan, brown, and red. The units generally contain large amounts of volcanic detritus, ranging in size from small ash particles to lava boulders a meter or more across, and most of the ash component is altered to clay. A few thin beds of dark-brown carbonaceous shale and lignite, which are as much as a meter thick, are present in the lower part of the unit in the northeastern part of Helena Valley west of Hauser Lake. The deposits were laid down along ancient stream courses and in lakes that existed in the valley 2 to 38 million years ago.

Perhaps as much as half of the unit is made up of light-green, greenish-gray, gray, and light-reddish-gray clay in beds that are several centimeters to as much as 3 m thick. These clays represent altered volcanic ash and probably consist largely of the clay minerals montmorillonite and beidellite. Such clays are called bentonite. Clays of this sort are exposed in the ravine east of St. Peter's Community Hospital, in the ravine north of the Fish and Game Commission Building, and on the east side of Dry Gulch along upper Davis Street in the city of Helena. The bentonitic clays form smooth, rounded outcrops and swell when wetted; they are soft and easily eroded. Weathered surfaces generally have a crinkled or popcornlike texture due to expansion and shrinkage of the clay.

Beds of gray, brown, reddish-orange, and tan silt, sand, and gravel, which are interlayered with the clays at various horizons, form about 40 percent of the deposits. The sands are generally coarse and form beds as much as 3 m thick. They are mainly composed of grains of quartz, chert, feldspar, and rock fragments, but some are gravelly and contain scattered pebbles as much as 2 or 3 cm across. In places the sands are cemented with calcium carbonate and are hard and compact. The gravels form lensing beds that range from about ½ m to 4 or 5 m thick. They are common in exposures in the southeastern part of Helena Valley south of York Road. The gravels consist of rounded pebbles, cobbles, and boulders of volcanic rock (traprock), granite, quartzite, shale, and rare limestone in a matrix of slightly cemented clayey sand. Probably all of the rock constituents in the gravels were derived from nearby bedrock in the surrounding mountains. Boulders as much as a meter across are present in some beds, but large boulders are uncommon and the bulk of the gravels are formed of pebble- and cobble-size stones.

In the area south and southwest of East Helena, the older stream and lake deposits consist mainly of white to light-gray, compact, siliceous volcanic ash. These rocks are well exposed in a road cut along U.S. Highway 12 about a kilometer west of East Helena. They are mainly composed of an aggregate of small pumice fragments and mineral grains—chiefly quartz, feldspar, biotite, and hornblende. In most places the pumice component is partly altered to clay, and the deposits are relatively soft and easily eroded. Some of the volcanic ash, however, is formed of coarse, angular volcanic rock fragments that are firmly cemented, and this material is hard and massive.

The older stream and lake deposits, which are firmly compacted and moderately cemented, appear as a whole to be quite stable in an engineering sense. Road cuts in these materials have experienced little failure by slumping, and high natural scarps along the valleys of Spokane Creek and its tributaries, which are formed in the deposits, have stood for many decades without appreciable change. The bentonitic clays that form a large part of the unit are probably more prone to failure by slumping and internal movement than other rock types, especially where saturated with water. Strong earthquake ground motion would tend to reduce the shearing resistance of the clays and promote failure by slumping and subsidence.

BEDROCK

Bedrock, which forms the solid rock foundation beneath the area, consists of sedimentary, plutonic, and volcanic rocks. Sedimentary rocks are those that have formed by cementation and hardening of water- and wind-deposited sediments; plutonic and volcanic rocks, collectively known as igneous rocks, are those that have formed by solidification of molten or partially molten material called magma. The plutonic rocks are the result of intrusion and crystallization of magma beneath the Earth's surface, and the volcanic rocks are the result of extrusion of magma as lava and solidified lava fragments on the Earth's surface. The distribution of the three types of bedrock is shown on plates 1 and 2. Most of the bedrock is highly rigid, strongly and permanently cohesive, and of high shearing and compressive strength. Because of these characteristics, it is mechanically stable and, unlike the surficial deposits, resistant to slumping, settling, or other types of ground failure.

SEDIMENTARY ROCKS

Sedimentary rocks occupy much of the mountain border around Helena Valley and underlie the city of Helena beneath a thin cover of surficial deposits (pl. 1). Essentially, these rocks form a great layered sheet several thousand meters thick that rests on the so-called crystalline basement of the Earth's crust. The sedimentary bedrock ranges from middle Late Cretaceous age (about 86 million years ago) to Middle Proterozoic age (about 1,600 million years ago).

The sedimentary rocks include sandstone, shale, limestone, and dolomite. The sandstone is composed mainly of small grains of quartz, feldspar, and mica that are cemented by silica or by calcium carbonate (calcite). Much of the sandstone in the Helena area is bonded with silica to form a hard, massive rock called quartzite. The shale consists largely of minute, clay-size particles of quartz, feldspar, mica, and chlorite bonded with silica or calcite. Most of the shale in the Helena region is hard, firm, and thinly layered and resembles slate. The limestone is formed mainly of calcium carbonate, and much of it consists of the fragments of shells of marine organisms in a cement of calcite. It is mostly hard, firm, and compact. The dolomite, which outwardly resembles limestone, consists largely of calcium-magnesium carbonate (dolomite), and some of it is made up of the skeletal remains of marine algae. It is generally hard and massive and forms most of the bedrock beneath Helena.

All of the sedimentary rocks are characterized by a layered structure known as stratification. This structure is the result of deposition of the sediments in successive layers that vary somewhat in grain size, composition, and thickness. The surfaces between the layers are called bedding planes. The stratification of the sedimentary rocks in the Helena area is generally inclined at moderate to steep angles as a consequence of bending and tilting of the rocks by forces that formed the Rocky Mountains. Most of the sedimentary rocks are traversed by narrow joints that cut across the stratification. The rocks tend to split along these joints and along the bedding planes and commonly break down naturally at the surface into large and small fragments that in places veneer the solid rock.

PLUTONIC ROCKS

The plutonic rocks are mainly present in the high mountains along the southern border of the area where they form a great body of rock called the Boulder batholith (pls. 1, 2). Smaller masses are present in the terrain south and west of Helena Valley, such as the body that forms the center of the Scratchgravel Hills (pl. 1), and a small mass of plutonic rock is present beneath Carroll College in the city of Helena. Originally, these rocks were covered with great thicknesses of sedimentary and volcanic strata. Deep erosion has since exposed them at the surface. The plutonic rocks range from early Tertiary age (about 45 million years ago) to Late Cretaceous age (about 78 million years ago).

The plutonic rocks consist of an intergrown aggregate of crystalline minerals and are generally hard, massive, and compact. They range from silica-rich types called quartz monzonite and granite, composed mainly of quartz and potassium feldspar, to silica-poor types called diorite and gabbro, composed mostly of pyroxene and sodium-calcium feldspar. The silica-rich types are by far the more abundant. Most of the plutonic rocks are coarsely crystalline, but some are fine grained and a few are glassy. In some places, especially in areas of gentle topography, they are deeply altered to granular soil as much as a meter or two thick. This material is soft and loose and has the consistency of sand or fine gravel. Beneath the soil a zone of partially weathered rock called saprolite is generally present that grades downward into solid rock. The saprolite is more than a meter thick in some areas.

VOLCANIC ROCKS

The volcanic rocks mainly cover areas in the Elkhorn Mountains to the southeast and areas along the upper part of Tenmile Creek to the southwest where they form layered piles as much as 600 m thick. They are of Late Cretaceous age and between about 74 and 80 million years old. The volcanic rocks consist mainly of hard, massive lava and lavalike rock called welded tuff, but include some volcanic breccia, tuff, and conglomerate formed of lava fragments. They range from silica-rich types called rhyolite and rhyodacite to silica-poor types called andesite and basalt. The rhyolite and rhyodacite, which are the most abundant, are formed chiefly of a fine-grained aggregate of quartz and potassium feldspar. The andesite and basalt are made up largely of small crystals of pyroxene, sodium-calcium feldspar, and magnetite.

FAULTS

GENERAL CHARACTERISTICS

Geologic faults are fractures in the Earth's crust along which there has been displacement of the rock on one side relative to the rock on the other side in a direction parallel to the fracture. The surface along which the rock masses have moved is called the fault plane, and the intersection of the fault plane with the ground surface is called the fault trace. Faults are generally classified on the basis of the relative direction of movement of the crustal blocks that bound them. In the Helena area, three principal types are present: normal faults, thrust or reverse faults, and strike-slip faults. The diagrams presented in figure 2 illustrate the main characteristics of each type. Normal faults (fig. 2*A*) are those along which the block above the fault plane has moved downward relative to the block beneath the fault plane. Thrust or reverse faults (fig. 2*B*) are opposite and comprise those along which the block above the fault plane has moved upward relative to the block below. Normal faults are usually inclined more than 45°; thrust or reverse faults

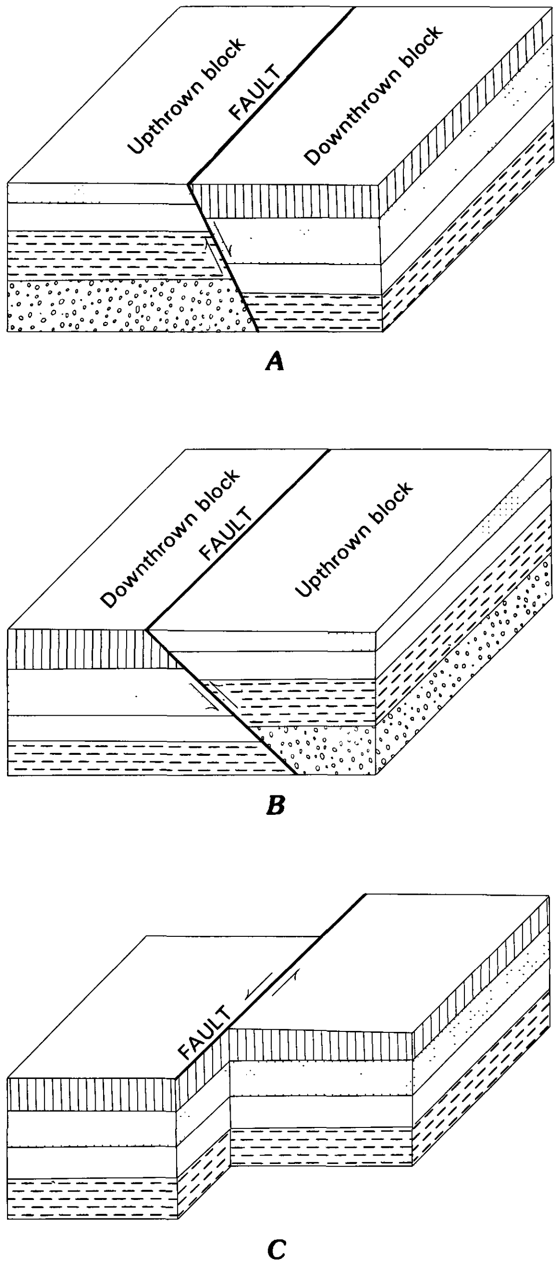


FIGURE 2.—Diagrams illustrating the principal types of faults in the Helena area. Arrows show relative direction of movement. *A*, Normal fault. Block to right of fault has moved downward with respect to block on left. *B*, Thrust or reverse fault. Block to right of fault has moved upward with respect to block on left. *C*, Strike-slip fault. Blocks have moved horizontally past each other along the fault.

may be inclined more, or less, than 45°. Strike-slip faults (fig. 2*C*) are those along which blocks on either side of the fault plane have moved horizontally relative to each other. Such faults are generally vertical or steeply inclined.

Movement on most faults, especially on the larger ones, takes place over a long period of time. On some faults the movement progresses slowly by a succession of small displacements separated by periods of inactivity; on others it occurs by imperceptibly slow, continuous movement called fault creep. Sudden breaks with surface displacements of a few meters and more have occurred on faults during strong earthquakes. Most faults are formed during periods of deformation that affect large regions of the Earth's crust; activity on the faults then ceases. In certain regions, however, faults have been rejuvenated after long periods of inactivity.

Faults are often classified as active or inactive on the basis of their history of displacement. Active faults are those on which movement has taken place in the recent geologic past and on which movement is likely to occur in the future. The "recent geologic past" is commonly understood to mean the Holocene Epoch of geologic time between 0 and 10,000 years ago (Bonilla, 1970, p. 68-69). Inactive faults are those on which movement occurred in some earlier period of Earth history and which show no sign of displacement in Holocene time.

Active faults may be marked by historic surface displacement, by the offset of surficial deposits or landforms of geologically recent age, or by the presence of fault-produced topography such as recently formed scarps, offset stream courses, water-filled depressions, linear ridges, and narrow trenches. The absence of these features does not necessarily indicate that a fault is inactive, however, for geologic processes of erosion and deposition may effectively obliterate the physiographic evidence of fault displacement within a short period of time. Significant displacements that are not reflected at the Earth's surface also may occur on active faults at depth. In general, most faults are difficult to classify as active or inactive because the geologic record of their movement is incomplete. At the present state of knowledge, we cannot determine with certainty whether a given fault will undergo movement in the future.

Earthquakes are commonly associated with faults and are generally considered to result from instantaneous rupture and movement on fault planes beneath the Earth's surface. In earthquakes of low to moderate magnitude, the rupture ordinarily is confined to a local area on the fault surface within the crust, but in shocks of high magnitude the rupture may extend widely over the fault surface and culminate in displacement at ground level. Additionally, ground motion generated by a large earthquake on one fault has in some instances caused reactivation of other adjacent faults and resulted in extensive breakage, warping, and subsidence of the land. Deformation of that sort occurred during the Hebgen Lake, Montana, earthquake of 1959 (Witkind, 1964b).

All faults, whatever their age and whether they are active or inactive, represent surfaces or zones of potential failure in rocks of the Earth's crust. Accordingly, in highly seismic regions, every fault probably should be considered as a hazard. The degree to which an individual fault constitutes a hazard depends on such variables as the location, length, depth, and displacement of the fault and whether it is active or inactive. Long, active faults that extend to great depth are usually the most hazardous.

Faults are abundant in the Helena area. Some are of very large displacement, but few are discernible on the ground, for they are largely covered with soil or loose rock or are concealed beneath surficial deposits. Most are confined to bedrock, chiefly sedimentary and volcanic bedrock, but some displace surficial deposits. Most of the faults have been recognized by the offset of rock formations on opposite sides of their trace; a few are marked by prominent topographic scarps resulting from displacement of the ground surface.

Only a superficial study of the faults in the Helena area has been made by the author, and little quantitative data exist on the precise extent and time of the latest movements on them. At present we lack evidence that any of the faults have undergone surface movement in Holocene time (last 10,000 years), and, accordingly, none of them can be classified as active according to the definition previously outlined. However, two major strike-slip faults, which seem to be responsible for much of the seismic activity in the Helena area, and several large normal faults, which displace surficial deposits of pre-Holocene age and which are marked by well-defined scarps, are categorized as potentially active faults. Other faults in the area, which generally lack physiographic or other indications of Holocene movement and which appear on the basis of geological evidence to have originated many millions of years ago, are considered to be inactive.

The location of faults in the Helena area is shown on plates 1 and 2 on which the fault traces are represented by heavy lines. The larger faults, some of which continue far beyond the report area, are named after prominent geographic features. A small-scale map showing the traces of the principal faults in and near the Helena area is presented in figure 3.

MAJOR STRIKE-SLIP FAULTS

It has long been recognized that a zone of fundamental crustal discordance extends from the vicinity of Helena, Montana, northwestward across western Montana and northern Idaho to eastern Washington. This zone, known as the Lewis and Clark line (Billingsley and Locke, 1939, p. 36; Harrison and others, 1974, p. 9; Reynolds, 1977; Reynolds and Kleinkopf, 1977; Reynolds, 1979, p. 191-192), separates crustal blocks of profoundly contrasting structural style and bulk rock composition that have been juxtaposed by a combination of large-scale vertical and horizontal fault movement. The term "line" was first applied to this structural feature by Billingsley and Locke (1939, p. 36) and is used for historical reasons. Actually, the "line" represents a zone 10–50 km wide that is characterized by faulting and other profound geologic discontinuities (Reynolds and Kleinkopf, 1977).

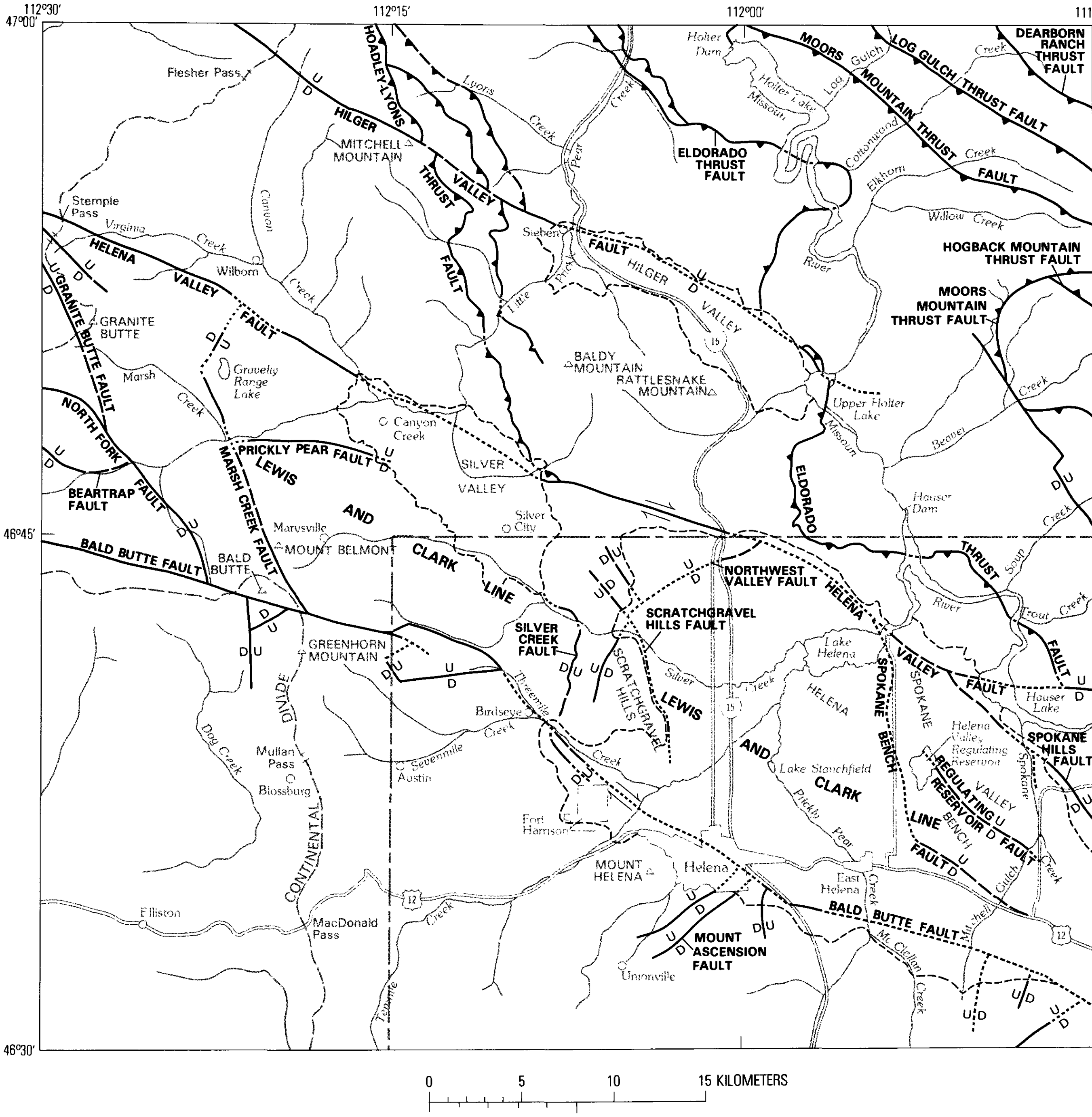
Two major strike-slip faults that are believed to mark the eastern segment of the Lewis and Clark line are present in the Helena area. One, named the Bald Butte fault, forms the southern boundary of the line; the other, named the Helena Valley fault, forms the northern boundary of the line (fig. 3).

The traces of the Bald Butte and Helena Valley faults are remarkable straight, and they are interpreted as steep fractures that extend far into the Earth's crust. South of the Bald Butte fault the land surface is mainly underlain by sedimentary, volcanic, and plutonic rocks. Large northeast- and northwest-trending folds and normal faults in the sedimentary and volcanic rocks of that area end sharply against the Bald Butte fracture. North of the Helena Valley fault the land surface is mainly underlain by sedimentary rocks. Broad northwest-trending folds and thrust faults in the rocks of that area terminate abruptly against the Helena Valley fracture. Between the Bald Butte and Helena Valley faults is a linear crustal strip 10-15 km wide that is composed mainly of sedimentary rocks. This strip is deformed into irregular folds and is broken by large normal faults, and it contains small, scattered masses of plutonic rock. Much of the seismic activity in the Helena area and in the adjoining region to the northwest appears to be concentrated along the Bald Butte and Helena Valley faults and within the deformed crustal strip between them, which constitutes the Lewis and Clark line (fig. 10).

BALD BUTTE FAULT

The Bald Butte fault, recognized during the course of this study, seems to have been the locus of many small earthquakes in 1973 and may be the most seismically active fracture in the area. The fault is named for Bald Butte, a prominent peak along the Continental Divide southwest of Marysville (fig. 3), where the fracture is well exposed.

In the Helena area, the trace of the Bald Butte fault extends from the headwaters of Threemile Creek, at the northwestern boundary of the area, southeastward through the community of Birdseye to a point about 1 km north of Fort Harrison on the western outskirts of Helena (pl. 1). Southeast of that point the trace of the fault is covered by surficial deposits, but it is inferred to extend beneath those materials and to join a fault exposed



EXPLANATION

STRIKE-SLIP FAULT—Arrows show inferred relative direction of horizontal movement. Dashed where inferred; dotted where concealed

NORMAL FAULT—U, upthrown side; D, downthrown side. Dashed where inferred; dotted where concealed

THRUST FAULT—Sawteeth on upthrown side. Dashed where inferred; dotted where concealed

OUTLINE OF INTERMONTANE BASIN

BOUNDARY OF HELENA AREA AS DEFINED IN THIS REPORT

FIGURE 3.—Map showing the traces of principal faults in and near the Helena area. Northeast corner in part from unpub. mapping of M.W. Reynolds (1978).

in bedrock about 6 km southeast of Helena (pl. 2). Farther east, the location of the Bald Butte fault is more speculative. Probably it extends eastward along the southern margin of Helena Valley, joins an east-west tear fault along the northern front of the Elkhorn Mountains described by Smedes (1966, p. 96; pl. 2, this report), and continues southeastward into Townsend valley. Northwest of the Helena area, the fault extends to Bald Butte in the Elliston quadrangle, continues westward across the Continental Divide north of Black Mountain, and reaches the northwest border of Avon Valley where it is covered by surficial deposits. Beyond that point the location of the fault has not been accurately established, but reconnaissance studies suggest that it probably continues northwestward beneath the surficial fill in Avon Valley and joins a major northwest-trending fracture in the valley occupied by Nevada Lake.

A prime characteristic of the Bald Butte fault is the large variation in apparent displacement of rock strata along its trace within relatively short distances. For example, at Bald Butte (fig. 3), the fault displays an apparent vertical separation of more than 4,400 m, yet a few kilometers to the west the apparent offset is 200 m or less. Similar variations in apparent vertical displacement occur elsewhere along the trace farther west and to the southeast. Furthermore, the sense of relative vertical displacement on the fault changes along its trace. East of the Continental Divide, rocks on the north side of the fault appear to be generally displaced upward relative to the rocks on the south, whereas west of the divide rocks on the north side of the fault appear to be displaced downward relative to the rocks on the south. This relation, together with the sharp change in regional geology across the fracture, strongly indicates that the main movement on the Bald Butte fault was strike slip, the rocks south of the fault perhaps moving west relative to the rocks on the north and the horizontal translation amounting to several kilometers. However, matching structures or matching rock strata on either side of the fault that might indicate the true sense of movement and absolute displacement on the fracture have not been identified.

In places, rocks adjacent to the Bald Butte fault are steeply tilted, extensively shattered, traversed by closely spaced joints, and cut by numerous, steep secondary faults, some of which extend several tens of meters from the main fracture. These secondary structures were probably produced by strike-slip movement. They are particularly well developed along the fault trace in the vicinity of Birdseye.

Evidence of geologically recent or historic movement along the Bald Butte fault is lacking. Topographic features indicative of surface breakage have not been observed, and along much of its course the fault appears to be covered by surficial deposits of Holocene and Pleistocene age (0–2 million years ago) and by older stream and lake deposits of middle and late Tertiary age (2–38 million years ago). However, further work is necessary to determine with certainty that these rocks have not been broken by recurrent movement on the fracture. For example, it is possible that small displacements of the ground surface along the trace of the fault at the southern margin of Helena Valley have been obliterated by the activities of man. In general, geologic relations suggest that the principal movement on the Bald Butte fault predated the formation of the older stream and lake deposits and took place more than 38 million years ago.

Despite its apparent geologic antiquity, the Bald Butte fault is considered to be potentially active, for low-magnitude earthquake activity, which was localized along it in 1973 (fig. 10), suggests that the fracture is undergoing continuous or renewed adjustments at depth. The coincidence of seismic activity with the fault is described in the section on "Seismic history of the Helena area."

HELENA VALLEY FAULT

The Helena Valley fault is well exposed along the northwestern margin of Helena Valley and in the low range of hills between Helena Valley and Silver Valley in the Rattlesnake Mountain and Silver City quadrangles, where it was discovered and mapped by M.L. Bregman and G.D. Robinson in 1970. Northwest of this exposure, the fault extends along the northeastern margin of Silver Valley, crosses the terrain northwest of the community of Canyon Creek, and continues to the Continental Divide near Stemple Pass (fig. 3). Beyond that point the location of the fault is uncertain, but satellite imagery suggests that it extends through a large area of volcanic rocks of probable Oligocene age (25–38 million years ago) north of Stemple Pass and continues northwestward to join the St. Marys fault (Harrison and others, 1974, fig. 3), which defines the northern limit of the Lewis and Clark line across much of northwestern Montana. To the southeast, the fault is poorly exposed, but geologic studies indicate that it extends along the northern border of Helena Valley, traverses older stream and lake deposits west of Hauser Lake, crosses the Missouri River, leads up Market Gulch, and continues eastward into Townsend valley in the adjoining Canyon Ferry quadrangle.

The type and amount of displacement on the Helena Valley fault probably compare with displacement on the Bald Butte fracture. Reynolds (1977) postulated that movement on the Helena Valley fault has varied through geologic time, from dominantly vertical between 1100 and 700 million years ago to dominantly strike slip during more recent geologic time. During the latter time, rocks north of the fault moved east relative to the rocks on the south, the horizontal translation amounting to several kilometers. However, the absolute displacement on the fault in the Helena area cannot be determined from existing geologic data.

Pronounced breakage of the rocks along the trace of the Helena Valley fault was observed in Market Gulch and farther east in the Canyon Ferry quadrangle. At these places the fault is represented by a zone of sheared and broken shale as much as 50 m wide enclosing large exotic masses of quartzite and limestone.

Physiographic features indicative of surface movement within the last few thousand years are lacking along the trace of the Helena Valley fault, and in places it is covered by stream deposits and slope wash of Holocene age (0–10,000 years ago). In the East Helena quadrangle (pl. 2), the fault cuts older stream and lake deposits of middle Tertiary age (25–38 million years ago), but the precise time of this movement has not been determined. The most recent movements on the Helena Valley fault in the Helena area are therefore bracketed between about 10,000 and 25 million years ago. The main movement on the fault is inferred to have taken place prior to the deposition of the Tertiary deposits more than 38 million years ago.

The epicenter of the main shock of the Helena earthquake of 1935 and the epicenters of several small earthquakes recorded in 1973 lie near the trace of the Helena Valley fault (fig. 10), a relation that suggests these shocks originated on the fracture. Accordingly, although geologic relations indicate that major displacement occurred far back in geologic time, it seems likely that the fault is now undergoing intermittent movement and may be considered an active break.

PRINCIPAL NORMAL FAULTS

The principal normal faults in the area are located in Helena Valley and west of the Scratchgravel Hills within the Lewis and Clark line (fig. 3). They include the Silver Creek, Northwest valley, Scratchgravel Hills, Spokane Bench, Regulating Reservoir, and Spokane Hills faults. The Silver Creek and Northwest valley faults appear to be old, inactive fractures. The Scratchgravel Hills, Spokane Bench, Regulating Reservoir, and Spokane Hills faults probably have undergone significant movement in Pleistocene time (10,000–2 million years ago). They are regarded as potentially active breaks.

SILVER CREEK FAULT

The Silver Creek fault is in the north-central part of the Helena quadrangle (pl. 1). It extends southward from Silver Creek through sedimentary bedrock west of the Scratchgravel Hills and terminates about 1½ km north of Sevenmile Creek east of Birdseye. Northwest of its exposure at Silver Creek, the fault is covered by surficial deposits and its precise location is unknown, but probably it continues a long distance northeastward beneath the surficial materials along Silver Creek. The fault is inclined steeply southwest and is downthrown on the west and southwest. At Silver Creek, dolomite on the southwest side of the fault is dropped down against shale on the northeast and the displacement is at least 600 m. South of Silver Creek, displacement on the fault decreases progressively and becomes zero at its termination north of Sevenmile Creek. Where the fault crosses County Highway 279 (Lincoln Road) near the center of sec. 16, T. 11 N., R. 3 W., on the north side of Silver Creek, the rocks on either side of the break are intensively sheared and shattered and form a zone of deformation about 3 m wide. It cannot be determined, however, whether actual movement was confined to one or the other of the bounding blocks or whether both were active during fault movement.

The Silver Creek fault has no obvious association with contemporary seismic activity, displays no evidence of movement in Holocene time (last 10,000 years), and does not appear to cut surficial deposits northwest of its exposure along Silver Creek. Accordingly, it is considered to be inactive.

NORTHWEST VALLEY FAULT

The Northwest valley fault extends northward along the western side of the Scratchgravel Hills, continues northeastward across the northwestern part of Helena Valley, and terminates against the Helena Valley fault (pls. 1, 2). The fault is concealed beneath surficial deposits over much of its length, is exposed only at its west and east ends, and is inferred to be offset by the Scratchgravel Hills fault. The fracture is steeply inclined and is downthrown to the south and east. It has a vertical displacement of at least 200 m and perhaps as much as 300 m, as indicated by the offset of rock formations along its trace. At the southwest, the fault presumably dies out in sedimentary bedrock west of the Scratchgravel Hills. The fault has no topographic expression, shows no evidence of movement in Holocene or Pleistocene time (last 2 million years), and has no apparent association with recent seismic activity. It is therefore regarded as an inactive break.

A steeply inclined normal fault of northwest trend and a few kilometers long crosses secs. 3 and 11, T. 11 N., R. 4 W. north of the Northwest valley fault (pl. 1). This northwest-trending fault is inferred to end against the Northwest valley fracture and is considered to be inactive.

SCRATCHGRAVEL HILLS FAULT

The Scratchgravel Hills fault extends along the eastern front of the Scratchgravel Hills in the northeastern part of the Helena quadrangle (pl. 1). This fault was first identified by Pardee (1950, p. 382-383), who assumed that the steep, straight eastern face of the hills was a scarp produced by fault movement. The fracture presumably lies at the eastern foot of the hills where it is largely covered by stream deposits and slope wash. At the south, the fault extends an unknown distance into Helena Valley beneath the surficial materials. At the north, its location is also uncertain, but it is inferred to cut the Northwest valley fault and to continue a few kilometers northwestward in sedimentary bedrock. The fault probably is steeply inclined to the east, is upthrown to the west, and is inferred to cut older stream and lake deposits that lie beneath younger stream deposits and slope wash north and south of the Scratchgravel Hills (pl. 1). Pardee (1950, p. 383) estimated that displacement on the fault was at least 300 m, as measured by the height of the scarp along the Scratchgravel Hills, but precise geologic data are not available to determine the true slip on the fracture.

The stream deposits and slope wash that cover the trace of the Scratchgravel Hills fault are of Holocene age (last 10,000 years). These materials show no evidence of movement along the line of the fault, which suggests that major fault displacement occurred prior to Holocene time. No additional geological data are available on the time of movement except that the fault probably cuts older stream and lake deposits of middle Tertiary age (25-38 million years ago). However, if the scarp at the east face of the hills was generated by the fault movement, the main displacement may have taken place in Pleistocene time, between 10,000 and 2 million years ago, for the scarp is in a youthful state of erosion. Furthermore, movement on the fault may not have ceased entirely, for the epicenters of two small earthquakes that occurred in 1973 lie at the south end of the fracture and another lies along the northern trace (fig. 10). These earthquakes may have originated on the fault. Accordingly, in view of its probable Pleistocene age and possible association with historic earthquakes, the Scratchgravel Hills fault may be considered an active break.

SPOKANE BENCH FAULT

The Spokane Bench fault trends northward through Helena Valley in the central part of the East Helena quadrangle (pl. 2). It extends west-northwest from its apparent southern limit near Clasoil, northward along the west side of the topographic highland known as Spokane Bench, northwestward across the east end of Lake Helena, and terminates against the Helena Valley fault north of the lake. It is about 20 km long. Over most of its length, the fault displaces older stream and lake deposits and follows the base of a low scarp that bounds Spokane Bench on the south and west. This scarp, which was produced by the fault movement, generally marks the fault trace. On the south side of the bench, the low, south-facing scarp interrupts the smooth, northwardly inclined surface formed along the southern margin of Helena Valley. On the west side of the bench, stream deposits of Holocene age (last 10,000 years) are laid down against the base of the scarp and the fault is concealed beneath them. To the north, in the vicinity of Lake Helena, the scarp is formed in bedrock.

The Spokane Bench fault is steeply inclined, and presumably it cuts and displaces the bedrock floor beneath Helena Valley. Displacement on the fracture appears to increase progressively northward along the fault trace from near Clasoil where it has zero displacement. Vertical displacement at the surface 5 km west of Clasoil is at least 20 m, as indicated by the height of the fault scarp at Diehl Lane. Along its midlength, west of the Helena Valley Regulating Reservoir, the vertical slip may amount to 30 m or more, as indicated by the scarp height. At the north, vertical displacement on the fracture is perhaps as much as 100 m where older stream and lake deposits are dropped down against sedimentary bedrock.

As part of a seismic risk investigation undertaken by the U.S. Bureau of Reclamation in 1977, trenches were excavated a short distance east of and at the foot of the Spokane Bench fault scarp in the vicinity of the Helena Valley Regulating Reservoir. A detailed study of those trenches, which were as much as 80 m long and 2 m deep, was made by M.W. Reynolds of the U.S. Geological Survey and M. McKeown, U.S. Bureau of Reclamation. They observed that older stream and lake deposits of middle to late Tertiary age (2-38 million years ago) in the upper part of the scarp dip as much as 70° northeast (away from the scarp) and that sediments of probable early Pleistocene age (Pleistocene age = 10,000-2 million years ago) near the foot of the scarp are intensely folded, slumped along curving fractures, locally shattered, and in places invaded by sand dikes (M.W. Reynolds, written commun., 1977). Presumably, this deformation was caused by movement on a concealed, west-dipping fault at the base of the scarp—the Spokane Bench fault—during the middle or latter part of the Pleistocene Epoch. The Pleistocene displacement establishes the fault as a potentially active break. Conceivably, the fault is now undergoing displacement by slow creep.

Although the Spokane Bench fault has no record of historic seismic activity, the sand dikes in the deformed sediments of Pleistocene age, a short distance east of the concealed trace of the fracture, are probably related to strong earthquakes of local origin. These dikes, which are steeply inclined, of tabular shape, and as much as 20 cm wide, are believed to be the result of earthquake-induced liquefaction of sand at shallow depth and its injection into fractures in the overlying sediments (M.W. Reynolds, written commun., 1977). The age of the sand dikes could not be determined, but possibly they were formed during the destructive earthquake of 1935, at which time local residents saw water and sand spouting from cracks in the ground surface along the line of the fault north of the trenching site (M.W. Reynolds, oral commun., 1977). On the other hand, the dikes may relate to an earlier strong earthquake that took place in the Helena area long before the settlement of Montana.

REGULATING RESERVOIR FAULT

The Regulating Reservoir fault, which was recognized by M.W. Reynolds in 1975, trends northwest across the central part of Spokane Bench in the East Helena quadrangle (pl. 2). It is about 6 km long, extends from the east side of the Helena Valley Regulating Reservoir at the north to Mitchell Gulch at the south, and crosses Canyon Ferry Road. Along most of its length, the fault follows the base of a prominent, west-facing scarp produced by vertical movement on the fracture. This scarp breaks the old land surface on Spokane Bench, and the displacement has produced a pronounced eastward tilt of the ground surface on either side of the fault trace. The offset of the land surface, as marked by the height of the scarp, ranges from 12 to 30 m, which is a rough measure of the minimum vertical displacement on the fracture.

The age of the Regulating Reservoir fault cannot be accurately determined from existing geologic data. The fracture displaces older stream and lake deposits of probable Oligocene (middle Tertiary) age (25-38 million years ago) along much of its trace and extends beneath stream deposits of Holocene age (last 10,000 years) at Mitchell Gulch. Movement on the fault therefore occurred between 10,000 and 25 million years ago. It is probable, however, that the movement took place during the latter part of that interval, for the resulting fault scarp is a young landform little modified by erosion. Possibly the fault formed more or less simultaneously with the parallel-trending Spokane Bench fault, which cuts Tertiary strata and displays evidence of Pleistocene activity. It seems advisable, therefore, pending the acquisition of more conclusive age data, to classify the Regulating Reservoir fault as a potentially active fracture.

SPOKANE HILLS FAULT

The Spokane Hills fault is in the northeastern part of the East Helena quadrangle (pl. 2). It extends northwestward along the west margin of the Spokane Hills, crosses Spokane Creek and the York Road, and ends against the Helena Valley fault. The Spokane Hills fault cuts sedimentary bedrock at the south, displaces older stream and lake deposits down against sedimentary bedrock along its midlength, and traverses older stream and lake deposits at the north. Between Canyon Ferry Road and Spokane Creek, the fracture follows the base of a remarkably steep, straight scarp in the bedrock that probably was produced by a combination of fault movement and differential erosion on either side of the fault trace. The true displacement on the fault cannot be determined from current data, but geologic relations suggest that the minimum vertical movement on the fracture was several hundred meters.

Major movement on the Spokane Hills fault apparently occurred more than 20,000 years ago, for in places the fracture is covered by glacial-lake and wind-laid deposits of about that age, which show no evidence of displacement. However, the fault must have originated not long before the deposition of those sediments, for the scarp along its trace is little eroded and is in a youthful geologic state. Moreover, M.W. Reynolds (oral commun., 1977) has noted that the bedding is abnormally steep in newly formed, fan-shaped deposits of mixed stream and slope debris along the northern base of the scarp, which suggests that movement on this portion of the fracture may have continued into Holocene time (last 10,000 years). The fault is therefore regarded as a potentially active break.

A splay from the Spokane Hills fault is inferred to extend southward beneath stream deposits along Spokane Creek (pl. 2).

SECONDARY NORMAL FAULTS

Many normal faults of shorter length and generally of smaller displacement than those just described are present in the area and are shown on plates 1 and 2. They are mostly formed in sedimentary and volcanic bedrock to the south and west of Helena Valley, and several are near Helena. All appear to be inactive, for they are deeply eroded faults that show no evidence of movement in geologically recent or historic time and are not known to be associated with seismic activity. Only a few of the faults cut plutonic bedrock, and several of them end against plutonic contacts. This relation suggests that most of them originated in response to intrusion of the Boulder batholith and its satellitic masses some 68-78 million years ago (Tilling and others, 1968, p. 688), and, accordingly, they are at least that old. On the other hand, even though these geologically ancient faults are considered to be inactive, renewed movement on them in the future cannot be ruled out.

FAULTS AT WILLIT RIDGE

A prominent set of normal faults bounds a large wedge-shaped block of sedimentary bedrock in the vicinity of Willit Ridge in the northwestern part of the Helena quadrangle (pl. 1). The bedrock block is raised upward along these faults and is tilted downward against the Bald Butte fault, which bounds the block on the northeast. The normal faults may be second-order shears that developed simultaneously with the Bald Butte fracture. The fault bounding the south side of the uplifted block cuts the north end of a large mass of plutonic bedrock that is probably of Eocene (early Tertiary) age (between 38 and 55 million years ago). The maximum displacement on the Willit Ridge fractures is about 600 m, as measured by the offset of rock formations along their trace.

FAULTS NEAR AUSTIN

A conspicuous group of fractures is present in the vicinity of Skelly Gulch and Sevenmile Creek near the community of Austin in the west-central part of the Helena quadrangle (pl. 1). These faults bound a series of rectangular blocks of sedimentary bedrock between the Boulder batholith and small outlying bodies of plutonic bedrock, and probably are the result of uplift and collapse that occurred during emplacement of the plutonic masses. The displacement along several of these faults is as much as 60 m.

FAULTS AT HELENA

Five normal faults in and near the city of Helena have been mapped and described by Knopf (1913, pl. 7, p. 98; 1963). The largest of these fractures, called the Mount Ascension fault, extends northeastward from Dry Gulch along the southeast flank of Mount Ascension and disappears beneath slope wash a short distance east of Helena. It has a vertical displacement of about 230 m. West of that fault and parallel to it is a long fracture that runs from Orofino Gulch along the northwest flank of Mount Ascension and extends beneath slope wash in the eastern section of the city. It has a vertical displacement of about 70 m. Both of these fractures probably end against the Bald Butte fault. A small fault with a displacement of about 35 m splays off the fracture that runs along the northwest side of Mount Ascension, and this splay extends a short way into Helena beneath slope wash about a kilometer south of the State Capitol. Farther west, a fracture extends north-northeastward from the head of Last Chance Gulch along the eastern foot of Mount Helena to the reservoir on the west side of Helena, beyond which it is concealed by slope wash. The vertical displacement on this break is about 80 m. On the north slope of Mount Helena is a small fault with a vertical displacement of only a few meters. It disappears beneath slope wash at the southwestern margin of the city.

FAULTS WEST OF INTERSTATE HIGHWAY 15 AND NEAR MONTANA CITY

Several normal faults cut sedimentary bedrock in the hills west of Interstate Highway 15 and in the vicinity of Montana City in the southwestern part of the East Helena quadrangle (pl. 2). The largest of these fractures extends northward across the boundary between Lewis and Clark and Jefferson Counties and ends against the Bald Butte fault about a kilometer southeast of Helena. It is about 3 km long and has a maximum vertical displacement of about 200 m. Two small normal faults lie east of the southern trace of this fracture; other normal faults are found along the upper part of Holmes Gulch, between Clark Gulch and Jackson Creek, and south and east of Montana City. The displacement on these fractures ranges from a few meters to perhaps as much as 100 m.

FAULTS SOUTH OF LOUISVILLE STATION

A series of small normal faults, mapped initially by Smedes (1966, pl. 1), are distributed along the northern front of the Elkhorn Mountains south of Louisville Station in the southeastern part of the East Helena quadrangle (pl. 2). These fractures mainly trend north and northeast and are of short lateral extent. They cut sedimentary, volcanic, and plutonic bedrock. The largest fracture follows the north fork of Spokane Creek in the southeast corner of the quadrangle. Smedes (1966, p. 99) estimated the maximum vertical displacement on this break to be several hundred meters. Faults with a vertical displacement of 100 m or more also are present along Sheep Creek and along the upper part of Corral Creek. Other faults along the front of the Elkhorn Mountains are generally much smaller and have vertical displacements from a few meters to perhaps as much as 60 m. Several of the fractures, including the break along Sheep Creek, end abruptly against the Bald Butte fault.

CONCEALED ZONE OF NORMAL FAULTING IN HELENA VALLEY

On the basis of gravity measurements made in the eastern part of Helena Valley, a concealed zone of normal faulting has been postulated in the vicinity of Lake Helena (Davis and others, 1963). The location of the zone is shown on plate 2. The fault zone has not been verified by drilling or by seismic techniques, however, and is problematical. If the concealed fault zone is real, it might represent an old, long-inactive splay from the Spokane Bench fault, for the zone curves southeastward toward that fracture.

THRUST FAULTS

Four thrust faults are present in the Helena area—the Eldorado thrust fault, a thrust fault subsidiary to the Eldorado, the Soup Creek thrust fault, and a minor unnamed thrust fault. All are confined to the mountainous terrain in the northeastern part of the East Helena quadrangle (pl. 2). Other large thrust faults are present north and northeast of the area, the largest of which are the Hoadley-Lyons and Moors Mountain thrust faults (fig. 3). The thrust fractures are situated in the Montana disturbed belt, a broad zone of intricately folded and faulted rocks that extends from the Canadian border southward along the eastern front of the northern Rocky Mountains. Large thrust faults in the western part of this belt (for example, the Hoadley-Lyons and Eldorado thrust faults) appear to terminate at the Lewis and Clark line (fig. 3). The disturbed belt was formed during the later stages of the crustal disturbance that created the Rocky Mountains some 50-80 million years ago. There is no indication that any of the thrust faults in the belt have been rejuvenated in Holocene or Pleistocene time (last 2 million years) or that they have been associated with historic seismic activity. Consequently, they are considered to be inactive.

ELDORADO THRUST FAULT

In the Helena area, the trace of the Eldorado thrust fault extends eastward in the bedrock hills north of Lake Helena, bends sharply to the southeast at Eldorado Bar (after which it is named), and continues down the west side of the Big Belt Mountains to Market Gulch where it sharply ends against the Helena Valley fault (pl. 2). The Eldorado fracture is exceptionally well exposed where it crosses the Missouri River south of Eldorado Bar and again near the mouth of Trout Creek, north of York Road. North of the Helena area the fracture has been mapped in the Upper Holter Lake quadrangle by Robinson and others (1969), and a segment of the fault farther north has been described by Bregman (1976).

Along the Eldorado thrust fault the rocks to the south and west have moved up and over the rocks to the north and east a distance of several tens of kilometers, and the fracture extends far westward in the subsurface in the region north of the Helena Valley fault. The mass of rocks above the fault plane is called the upper plate of the thrust or the thrust sheet, and the mass of rocks below the fault plane is called the lower plate. The rocks that constitute the upper plate are bent into broad, gentle folds, whereas those that comprise the lower plate are crumpled into tight, closely spaced folds and are broken by subsidiary thrust faults of large and small magnitude. Following emplacement of the thrust sheet, the entire mass was subjected to further stress and the fault surface itself was warped. As a result, the trace of the Eldorado is quite sinuous (fig. 3), and the inclination of the fault varies in places from 20° to 50°. In general, however, the fault trends northwest and dips at a relatively low angle to the southwest.

At the fault trace, the upper plate of the Eldorado is formed of shale and the lower plate is formed of limestone, shale, sandstone, and quartzite. Along the east-west segment north of Lake Helena, the shale at the base of the upper plate is intensively crushed and shattered by the fault movement, forming a zone of breakage as much as 50 m wide, but along the southeast segment, between Eldorado Bar and Market Gulch, the rock at this horizon is sheared but not fragmented. This marked difference in style of deformation is probably related to the orientation of the fault with respect to the rocks in the lower plate. On the east-west segment, the thrust sheet cuts sharply across the stratification in the lower plate; on the southeast segment, it is essentially parallel to the stratification. Greater resistance to the fault movement on the crosscutting segment may have set up stresses in the overriding rock that caused the fracturing.

THRUST FAULT SUBSIDIARY TO THE ELDORADO

A thrust fault subsidiary to the Eldorado is present north of the trace of the Eldorado thrust in the terrain north of Eldorado Bar. This fracture marks the leading edge of a mass of younger sedimentary rocks several hundred meters thick that has been dragged across the underlying rocks by the Eldorado thrust sheet, perhaps as much as 2 or 3 km. The subsidiary thrust is inclined 10°-20° south, and its trace, though very sinuous, is generally parallel to that of the Eldorado. The fault is well exposed on the west side of the Missouri River along the road that leads to Hauser Dam. At that locality, white limestone in the upper plate rests on red shale and sandstone in the lower plate. The limestone is tightly folded, is broken by closely spaced joints, and is more intensely deformed than the rocks in the lower plate.

SOUP CREEK THRUST FAULT

The Soup Creek thrust fault cuts sedimentary bedrock north and south of Soup Creek, east of the Eldorado thrust fault. It trends northwest, dips 30°-70° southwest, and has a maximum displacement of several thousand meters. At the north, the fracture is folded in a broad arc and is cut by the subsidiary thrust along the Eldorado; to the south, it extends into the valley of Trout Creek and continues southeastward into the Canyon Ferry quadrangle. The Soup Creek thrust fault may have originated during a period of intense folding that preceded emplacement of the Eldorado thrust sheet.

MINOR THRUST FAULT

A small thrust fault about 2 km long and with a displacement of only a few hundred meters lies between the Eldorado and Soup Creek thrust faults. It appears to have resulted from breakage of a tightly compressed fold in the sedimentary bedrock and, like the Soup Creek fracture, may have formed before emplacement of the Eldorado thrust sheet.

NATURE OF EARTHQUAKES

Earthquakes are sudden vibrations of the ground surface caused by the passage of seismic waves through the Earth's crust. In most instances, the seismic waves are generated by slippage along geologic faults. The focus or hypocenter of an earthquake is the point in the Earth's crust where the fault rupture begins and from which the first seismic waves originate, the epicenter is the point on the Earth's surface directly above the focus, and the depth of focus (or focal depth) is the distance between the epicenter and the hypocenter. The relationship of these parameters is illustrated graphically in figure 4. Earthquakes generally occur in sequences that consist of one or more foreshocks, a main shock, and a large number of aftershocks. The focal depth of earthquakes ranges from 0 to 700 km. Calculated focal depths of earthquakes in Montana range from near the surface to about 20 km.

Two basic types of seismic waves are produced by earthquakes: body waves, which travel through the Earth, and surface waves, which travel along the Earth's surface. The body waves are the *P* or primary wave and the *S* or secondary wave. The *P* wave is compressional, like that of sound, in which each particle vibrates in the direction of propagation. It travels at a speed of about 5½ km/s in the upper crust. The *S* wave is transverse, like a radio wave, in which each particle vibrates at right angles to the direction of propagation. It travels about half as fast as the *P* wave. The surface waves, called the *L* or long waves, include the Love, Rayleigh, and other types of waves. They are generally of greater wavelength and period than the *P* and *S* waves. The Love wave produces lateral shear in the horizontal plane, and the Rayleigh wave produces an elliptical motion like that of wind-driven ocean waves. Love waves travel at about 4 km/s, and the Rayleigh wave is somewhat slower. In general, stronger ground motion is produced by body waves near the earthquake source and by surface waves at greater distance.

When seismic waves reach the Earth's surface they induce a highly irregular vertical and horizontal oscillation in the ground that may last from a fraction of a second to several minutes. The severity of the oscillation generally decreases with increasing distance from the earthquake source and is less for small earthquakes than for large earthquakes. Earthquake ground motion or ground shaking is extremely complex, and, in the source region, its duration and character depend not only on the magnitude of the shock and the distance from the source, but also on the physical properties of the rock and soil through which the seismic waves travel and on the geological structure of the earthquake site. Ground shaking is usually responsible for most of the structural damage that occurs during earthquakes. It also can trigger landslides and other types of ground failure such as settlement and cracking. Destructive waves in lakes, reservoirs, and rivers may also result from intense ground shaking.

The vibrations produced by earthquakes are recorded and measured by sensitive instruments called seismographs, which make a permanent, continuous record of the wave motions as a function of time. The seismograph records are called seismograms. The epicenter of an earthquake can be computed from the arrival times of seismic waves at three or more seismograph stations to an accuracy that depends upon the number and distribution of the stations. If the distribution of the seismograph stations is geographically unfavorable with respect to the earthquake source, the error in epicentral location may be as much as several tens of kilometers.

Strong-motion accelerographs are commonly installed in the basements of buildings in seismically active areas to measure the vertical and horizontal acceleration of the ground during earthquakes. These instruments record acceleration as a function of time, and it is usually expressed as a fraction of the acceleration of gravity (980 cm/s^2). The accelerograph records are called accelerograms. Velocities and displacements of the ground can be obtained by integrating the acceleration-time curves on an accelerogram. Such data are used by engineers in the design of earthquake-resistant structures and in the evaluation of the earthquake performance of structures.

The size of an earthquake is generally expressed in terms of magnitude, its local severity in terms of intensity. The magnitude of an earthquake is a measure of the energy released. Intensity is a measure of the local destructiveness of an earthquake. An earthquake therefore has only a single magnitude, but its intensity varies from place to place.

Earthquake magnitude is determined by measuring the amplitude of the trace of seismic waves on a seismogram. The concept was first introduced by Richter (1935, p. 7),

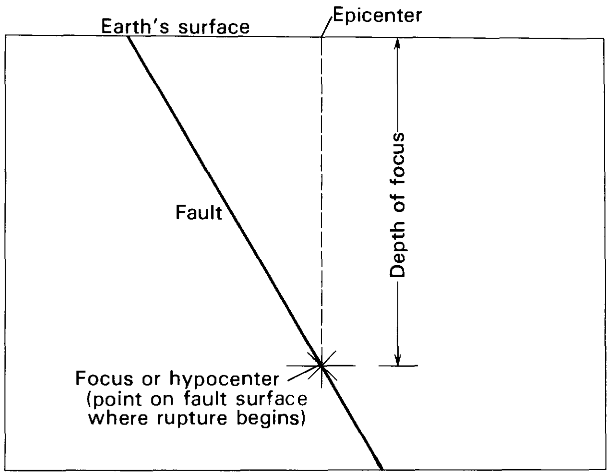


FIGURE 4.—Diagram showing the relation between epicenter, hypocenter or focus, and depth of focus of an earthquake. No scale.

who defined magnitude as the common logarithm of the maximum trace amplitude of seismic waves, in micrometers (1 micrometer = 0.001 mm), recorded on a Wood-Anderson torsion seismograph 100 km from the epicenter. Observations at distances other than 100 km were corrected to convert them to the standard distance. Richter magnitude was designed to measure the size of local earthquakes in California and could only be applied to shocks of relatively shallow focal depth within about 600 km of a recording station. It is designated as local magnitude, or M_L. Subsequently, two magnitude scales were evolved to compensate for distance and focal depth: the M_S scale, based on surface-wave amplitude and designed for earthquakes with geocentric distances of 20°–160° (station to epicenter) and with focal depths less than 50 km; and the M_b scale, based on body-wave amplitude and designed for earthquakes at geocentric distances greater than 5° and with focal depths between 50 and 700 km. In general, the M_S and M_b magnitude scales are reasonably consistent with Richter's M_L scale.

The standard surface-wave magnitude formula used by the U.S. Geological Survey is

$$M_S = \log_{10}(A/T) + 1.66 \log_{10} D + 3.3,$$

where A is the maximum horizontal surface-wave amplitude in micrometers, T is the wave period in seconds, and D is the geocentric distance in degrees (station to epicenter). The M_S scale is usually computed from Rayleigh surface waves in the period range of 18–22 s.

The standard body-wave magnitude formula used by the U.S. Geological Survey is

$$M_b = \log_{10}(A/T) + Q(D,h),$$

where A is the trace amplitude of a particular wave in the P-wave group, T is the wave period in seconds, and Q is a correction factor that is a function of geocentric distance (D) in degrees and focal depth (h) in kilometers. The M_b scale is generally computed from P waves having a period of 1 s.

Because magnitude scales are logarithmic, a unit increase in scale value is equivalent to a tenfold increase in the trace amplitude. For example, an earthquake of magnitude 8.0 represents a trace amplitude 10 times greater than that of a magnitude 7.0 earthquake, 100 times greater than that of a magnitude 6.0 earthquake, and so on. Although there is no upper or lower limit to magnitude, the largest ever recorded was 8.9 and the lowest about −3.

The relationship between the magnitude of an earthquake and the energy it releases is given by the equation (Richter, 1958, p. 366)

$$\mathrm{Log}_{10} E = 11.4 + 1.5M_S,$$

where M_S is the surface-wave magnitude and E is the energy in ergs. A difference of one whole unit in magnitude therefore corresponds to a factor of $10^{1.5}$, or 31.6, in the amount of energy released. Thus an earthquake of magnitude 8.0 represents an energy release that is about 32 times greater than that of a magnitude 7.0 earthquake and almost 1,000 times greater than that of a magnitude 6.0 earthquake.

Intensity is a measure of an earthquake's local severity as determined by its effect on people and manmade structures and the changes it induces in the Earth's surface. The principal intensity scale used in the United States is the Modified Mercalli Intensity Scale of 1931 (see appendix), in which the observed effects of earthquakes are grouped into a series of categories ranging from I to XII in order of increasing intensity. In large earthquakes, the intensity is "barely perceptible" at the fringe of the area over when the disturbance is felt, but becomes progressively greater toward the earthquake source where it may reach a level of "total damage." Intensity assignments are quite subjective, however, because no precise or well-defined set of rules exists for establishing them.

The level of earthquake intensity at any point is largely a function of distance from the earthquake source, earthquake magnitude, local duration of ground shaking, and soil conditions. Earthquakes that occur in remote, uninhabited regions generally cannot be evaluated in terms of Mercalli intensity.

The distribution of intensity at earthquake sites is commonly shown on maps by isoseismal lines, which are the estimated boundaries between regions of different Mercalli intensity rating outward from the epicenter. The area bounded by the innermost isoseismal line is the area of an earthquake where ground shaking is strongest. The data necessary to construct isoseismal maps are usually obtained by a systematic canvas of the local population in the affected area. In the absence of instrumental data, such maps may be used to locate earthquake epicenters and to determine their approximate magnitudes. These maps are also useful in defining broad differences in the shaking pattern in various areas and the relation of shaking to local earth structure—facts that are valuable in studies of earthquake hazards. The isoseismal map of the main shock of the Helena earthquake of 1935, shown in figure 5, is an illustration of this kind of map.

Earthquakes of magnitude greater than about 5.0 may be destructive. A magnitude 5.0 shock usually affects a relatively small area within a few kilometers of the epicenter. Within this area the duration of the stronger shaking may be only 1 or 2 s, yet such ground motion can be damaging to structures not designed to resist earthquake forces. An earthquake of magnitude 6.0 can produce damaging motion over an area of many hundreds of square kilometers and strong shaking that lasts for as much as 10 s. Helena, Montana, for example, was severely damaged by shocks of 6 and 6¼ in October 1935 (see following section), and an earthquake of magnitude 6.3, centered near Long Beach, California, in March 1933, ranks as one of the most destructive shocks in the history of the United States. Earthquakes of magnitude 7.0 or greater generally affect areas of thousands of square kilometers. In such shocks, intense ground shaking may last for several tens of seconds, and extensive ground breakage and landsliding usually occur. They often result in major disasters, such as San Francisco (1906), Tokyo (1923), Alaska (1964), and Guatemala (1976).

SEISMIC HISTORY OF THE HELENA AREA

GENERAL SUMMARY

In Montana, earthquakes occur chiefly in the western, mountainous part of the State. This area is part of a seismically active belt (the Intermountain Seismic Belt) that includes western Montana, southeastern Idaho, and western Utah. The belt generally parallels a series of large faults, some of which have undergone displacements in relatively recent geologic time. Most of the earthquakes that have occurred in Montana in historic time have been centered in four seismically active areas: the Flathead Lake area, the Helena area, the Townsend-Three Forks-Bozeman area, and the Virginia City-West Yellowstone-Lima area. Areas of lower seismic activity are scattered throughout western Montana. The plains region, in the eastern part of the State, is an area of very mild seismic activity. Only the earthquake history of the Helena area is considered here.

Several hundred earthquakes have been felt in and near the Helena area since it was first settled in 1864. The principal localities at which these earthquakes were noted include Helena, Kenwood (a Helena suburb), Fort Harrison, Rimini, Birdseye, Austin, Marysville, Silver City, Hauser Dam, East Helena, Montana City, Clancy, Alhambra, and Jefferson City. Most of the earthquakes have been of weak to moderate intensity (II-IV), but in 1935, a severe earthquake struck the area and caused extensive damage. The main shock and a strong aftershock in that earthquake were of intensity VIII.

The first earthquake on record in the Helena area was a strong shock of intensity VI in 1869. Other strong earthquakes, apart from those that occurred in 1935, include a shock of intensity IV-V in 1910, a sharp shock of intensity VI in 1925 (probably related to the Lombard earthquake), a jolt of intensity VI in 1930, and a strong shock of intensity VI in 1940 that was felt over an area of about 18,000 km^2. A notable increase in the general level of seismic activity (the number of minor earthquakes per year) occurred in 1945, during which a record number of 117 shocks were reported. Most of these were of weak (II-III) to moderate (IV) intensity, but a strong shock of intensity V on June 25, 1945, was felt over an area of 15,500 km^2. Most recently, the area was shaken by three sharp shocks on July 18 and 19, 1975. The strongest, which occurred on the 18th, had a magnitude of 3.9. The earthquake record in the area is much too short to identify or predict any cyclic recurrence of earthquakes. Activity at an intensity level of I-V is almost certain to continue in the future. The possibility exists that an earthquake of intensity VI or greater might occur at any time.

HELENA EARTHQUAKE OF 1935

The destructive earthquake at Helena in 1935 resulted in four deaths, about 50 injuries, and property damage of about $4,000,000 (Engle, 1936; Scott, 1936; Ulrich, 1936; Neumann, 1937). It consisted essentially of a strong foreshock of intensity VII on October 12, 1935, a main shock of magnitude 6¼ (intensity VIII) on October 18, and a powerful aftershock of magnitude 6 (intensity VIII) on October 31. On the basis of calculations from aftershock records, an epicenter lying about 5 km northeast of the center of the city at lat 46°37′N. and long 111°58′ W. was adopted as representing the central point of all activity (Neumann, 1937, p. 46). Recently, however, Dewey and others (1972, p. 888; fig. 5, p. 889) recomputed the epicenter of the main shock of October 18 using new techniques and found it to lie about 22 km north of the October 31 aftershock at about lat 46°48′ N. and long 112°01′ W. (fig. 10).

The earthquake of 1935 was characterized by an exceptionally large number of shocks—2,281 were recorded from October 3, 1935, to the end of 1936 (Neumann, 1937, p. 56). Of these, 62 were foreshocks and 2,218 were aftershocks. The strong foreshock on October 12 was felt over an area of 181,000 km^2, the main shock over an area of 596,000 km^2, and the powerful aftershock over an area of 363,000 km^2. Strong aftershocks of intensity VI on October 27, November 21, and November 28, 1935, and on February 13, 1936, also were felt over a wide area.

An isoseismal map of the main shock of the Helena earthquake of 1935 is shown in figure 5. The shock was felt over most of Montana, in southern Canada, over much of Idaho, as far west as Washington and Oregon, and south into Wyoming. The two small areas of low intensity outside the main area of disturbance, one in northwestern Washington and the other in southeastern Montana, have no obvious geological explanation.

The foreshock on October 12 caused damage of about \$50,000 in Helena, East Helena, and Fort Harrison. It toppled chimneys, cracked windows and plaster walls, and threw objects from tables and shelves.

The main shock of October 18 caused damage of about \$3,000,000 in Helena and East Helena and resulted in two fatalities and a few score injuries. Altogether, about 300 buildings in Helena sustained some form of serious damage from this shock; the fall of chimneys and brick veneer, the failure of gables, the cracking of windows and plaster, and the overthrow of objects were common throughout the city. Gravestones were twisted and overthrown in the cemeteries. Many large structures were extensively damaged by the main shock. These included two buildings at Intermountain Union College, the newly completed Helena High School, the Bryant Elementary School, the National Biscuit Company building, St. Joseph Orphan Home, the County Hospital, and the Kessler Brewery. Damage was slight to the State Capitol, the Federal Building, the St. Helena Cathedral, and the old high school.

The powerful aftershock on October 31 caused an additional several hundred thousand dollars' damage in Helena and East Helena and resulted in two fatalities. Many structures weakened by the previous shocks were further damaged by the aftershock, and the north wing of the new high school collapsed (fig. 6).

Damage in all of the shocks was mainly the result of ground shaking. Ground cracking was minor; only one small landslide was triggered; and a few rocks were dislodged and rolled down slopes in the mountainous areas.

A photograph of the new high school in Helena taken shortly after the October 31 aftershock is given in figure 6, and representative views of some of the other damage sustained in Helena during the earthquake are presented in figure 7. The most extensive type of damage to buildings was the collapse of brick, tile, and stone veneer and the collapse of walls made of these materials, which resulted in the fall of roofs. Solidly constructed wood buildings and steel-framed structures with walls built of heavy stone (for example, the State Capitol, the St. Helena Cathedral, the Federal Building) generally sustained the least damage. The drastic damage to the new high school was attributed to the fact that lateral earthquake forces were not considered in the design of the building (Scott, 1936, p. 10).

The aftershock on October 31 produced a horizontal ground acceleration of 115 cm/s^2, or about 12 percent of gravity, as measured by a strong-motion accelerograph installed in the basement of the Federal Building at Helena a few days after the main shock (Neumann, 1937, p.72). The portion of the accelerogram covering the principal motion of the aftershock is presented in figure 8. The maximum acceleration was on the north-south component, the duration of strong shaking was only about 3 s, and the vertical component of acceleration was generally less than either of the horizontal components.

The Federal Building at Helena is built on solid dolomite bedrock, and the recorded acceleration of 115 cm/s^2 probably applied only to that particular locality and type of rock. Ground-motion characteristics must have varied considerably from place to place during the major shocks, as indicated by the distribution of damage.

The earthquake produced a few small fissures in the ground surface (Scott, 1936, p. 14). Small cracks as much as several centimeters wide, 1 m deep, and 90 m long opened in gravel-surfaced roads near Lake Stanchfield, and, along the south and east shores of the lake, smaller cracks formed from which water and sand issued. A few cracks also formed in the floor of Helena Valley about 3 km northeast of Lake Stanchfield, one of which is shown in figure 9, and several small cracks opened near Clasoil in the southeastern part of the valley.

The earthquake had a pronounced effect on ground water. The flow of water from numerous wells and springs increased, and many new springs opened where none had previously existed. The flow of water in Sevenmile Creek and in Prickly Pear Creek increased by as much as 25 percent after the main shock (Ulrich, 1936, p. 331), but no record is available as to how long the abnormal flow lasted.

Small stationary waves formed in the gravel surface of upper Davis Street in the city of Helena during the 1935 earthquake (Ulrich, 1936, p. 334). The main shock on October 18 produced a group of waves that were oriented parallel to the street direction. They measured 64-71 cm from crest to crest and had a maximum trough depth of 5 cm. Following the major aftershock on October 31, the waves were more numerous and the troughs were enlarged to a maximum depth of 10 cm.

Visible ground waves were reported moving across the floor of Helena Valley by several persons during the strong earthquake shocks on October 18 and 31 (Ulrich, 1936, p. 334). Scott (1936, p. 12) reported that a man

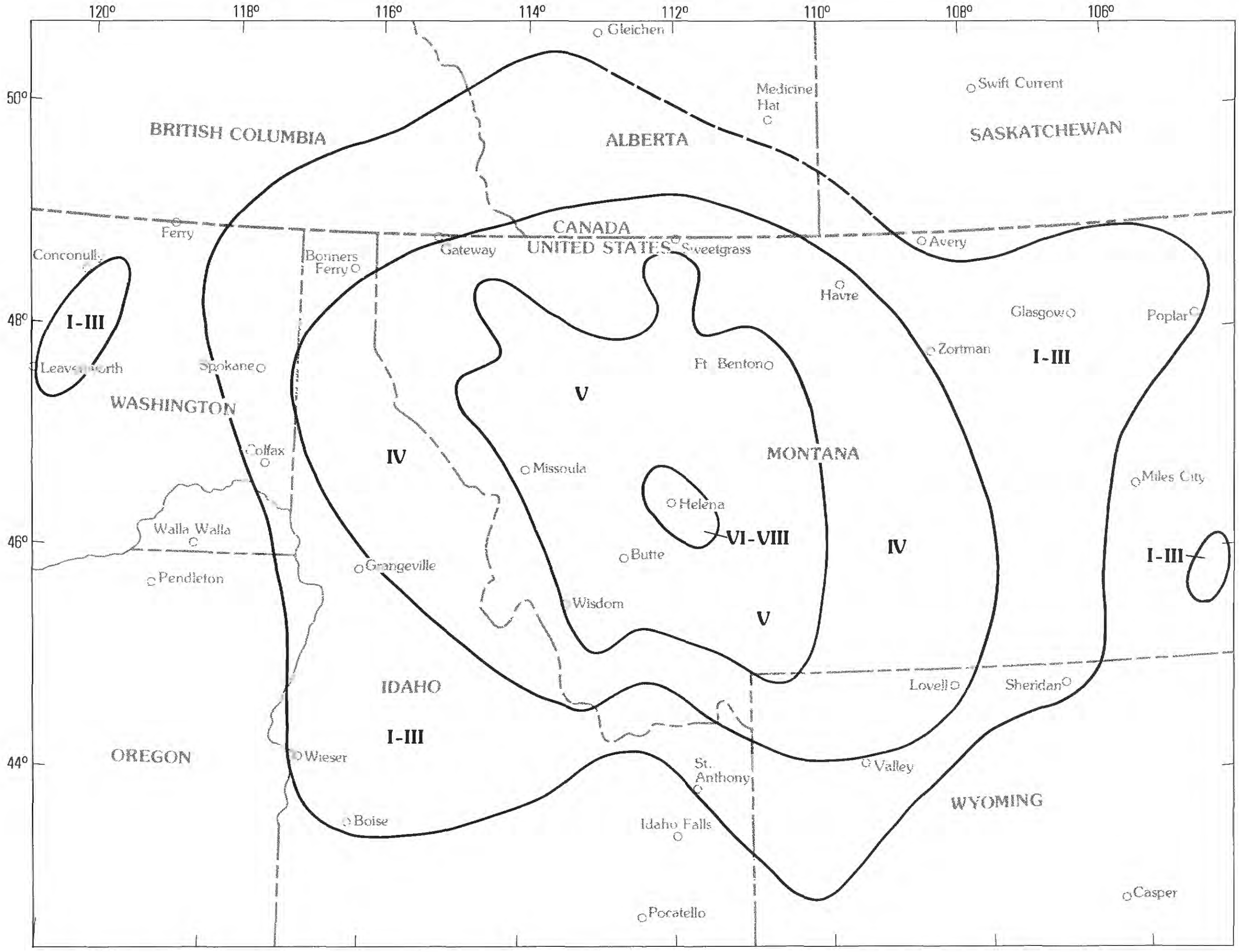


FIGURE 5.—Isoseismal map of the main shock of the Helena earthquake on October 18, 1935. From Neumann (1937, fig. 6).

standing in a field near Lake Helena on October 31 saw waves coming rapidly toward him and that he was thrown to the ground when they passed beneath his feet. This phenomenon, which has been reported in other parts of the world during large earthquakes, is not well understood. The seismic waves generated by an earthquake travel at much too great a speed to be observed and the ground motion produced by them is not a regular wave motion. It has been suggested that the appearance of visible waves may be an optical illusion caused when seismic waves emerge from the ground and change the refractive index of the air sufficiently to deflect light rays reaching an observer, the rapid changes in the ray path giving the ground an apparent wave motion (Richter, 1958, p. 131). However, the optical theory does not account for the man being forcibly thrown to the ground. Conceivably, his fall was a reaction to illusory waves.

LOCUS OF SEISMIC ACTIVITY

During a recent study of the Helena area (Freidline and others, 1976), in which seismic activity was monitored with portable seismographs, 97 small earthquakes were recorded from June 25 to August 18, 1973. The magnitudes of these earthquakes ranged from 0.0 to ±3.0, and focal depths ranged from near surface to about 17 km. Epicenters were located to an accuracy of ±2 to ±4 km. In the survey, it was found that most of the epicenters were clustered in two areas—one about 8 km northwest of Helena south of the Scratchgravel Hills and the other about 20 km northwest of Helena in the vicinity of Threemile Creek, at the northwest corner of the Helena quadrangle. Significantly, these areas of high seismic activity lie along the trace of the Bald Butte fault, and this relation strongly implies that the earthquakes originated

FIGURE 6.—View of the north wing of Helena High School following the major aftershock on October 31, 1935. This facility, newly completed in August 1935 at a cost of about $500,000, was severely weakened by the main shock on October 18. Photograph courtesy of the Montana Bureau of Mines and Geology.

on the Bald Butte fracture and that it may represent the locus of much of the current seismic activity in the Helena area. A plot of hypocenters of the earthquakes clustered south of the Scratchgravel Hills suggests that the fault plane dips about 60°S. (Freidline and others, 1976, p. 87).

The epicenters of some earthquakes that occurred in 1935 and 1973 and the traces of principal faults in and near the Helena area are plotted in figure 10. The remarkable concentration of epicenters along the trace of the Bald Butte fault south of the Scratchgravel Hills and at Threemile Creek is readily apparent, and several epicenters also lie near the trace of the fracture in the Elliston quadrangle farther west and in the East Helena quadrangle to the southeast. The destructive aftershock at Helena on October 31, 1935, also may have originated on the Bald Butte fault. As determined by Neumann (1937, p. 46), the epicenter of that shock lies about 3 km north of the fault trace, but, considering the margin of error inherent in the epicenter location, the aftershock may well have originated on the fracture.

The epicenter of the main shock of the Helena earthquake of 1935, as recomputed by Dewey and others (1972, p. 888), is near the trace of the Helena Valley fault as are several of the epicenters determined in the 1973 survey (fig. 10). Some of the 1973 epicenters also lie near the traces of the North Fork, Beartrap, Granite Butte, Marsh Creek, Prickly Pear, Hilger Valley, and Spokane Hills faults. Accordingly, these fractures may be seismically active and undergoing intermittent adjustment at depth. However, the frequency of seismic disturbance on them, as indicated by the plot of the 1973 epicenters (fig. 10), appears to be much less than the frequency of activity on the Bald Butte fault.

The epicenters determined in the 1973 survey are also significant from a regional standpoint, for they indicate that the earthquakes were mainly concentrated along and within the Lewis and Clark line (see section on "Major strike-slip faults"). West of the Helena area, historic earthquakes reaching as much as magnitude 5 have occurred along this zone in the vicinity of Helmville, Dalton Mountain, Greenough, Ovando, Bonner, Ninemile,

FIGURE 7.—Views of some damage in Helena, caused by the earthquake of 1935. *A*, Destruction of outer wall of County Hospital. *B*, Damage to brick wall of Bryant Elementary School caused by the main shock on October 18. Most of the remaining wall fell during the major aftershock on October 31. *C*, Collapse of building resulting from failure of walls. *D*, Outward fall of unbraced brick and tile walls and collapse of warehouse roof. *E*, Fall of stone gables. This type of failure was common. Photographs courtesy of Montana Bureau of Mines and Geology.

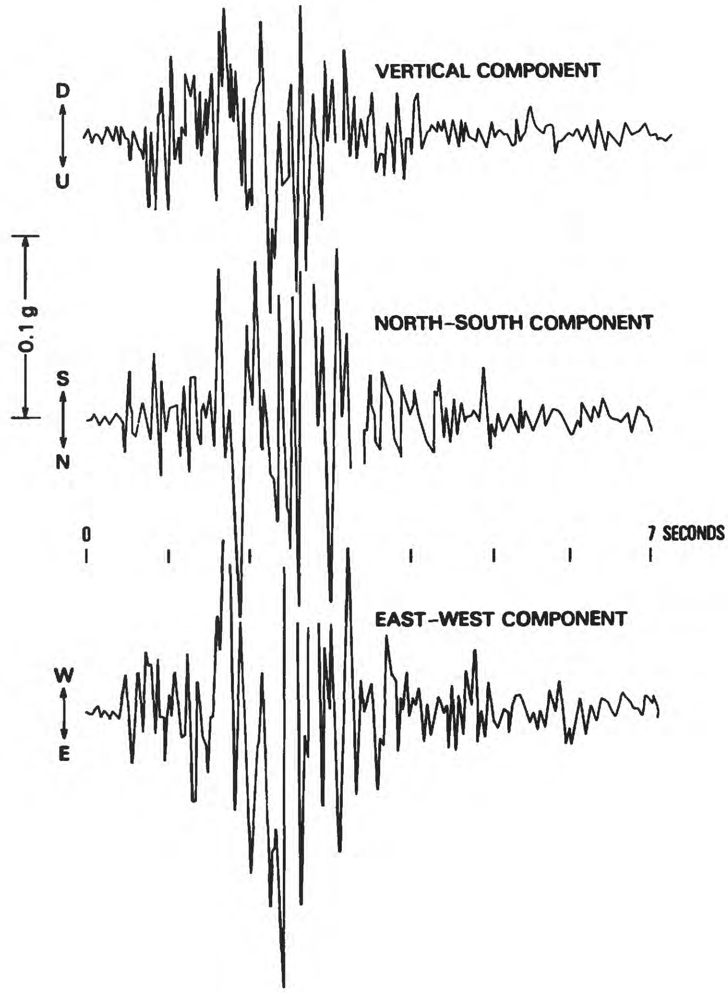


FIGURE 8.—Portion of accelerogram of the October 31 aftershock of the Helena earthquake of 1935. From Ulrich (1936, fig. 6).

Superior, and St. Regis, and numerous microearthquakes (small, instrumentally determined earthquakes), which resemble the swarm activity at Helena in 1945, have recently been recorded in the region around Ovando (Qamar, 1977, p. 756). This documented earthquake activity, together with geologic data developed by Reynolds and Kleinkopf (1977), supports the concept that the Lewis and Clark line is a regional locus of much of the earthquake activity in northwestern Montana and that it is a fundamental intracontinental crustal break along which active fault movement is now taking place.

SEISMIC RISK

Three destructive earthquakes of record have occurred in Montana besides the Helena earthquake of 1935. They include a magnitude 6¾ shock of intensity VIII in 1925 centered near Lombard in the northern part of Gallatin County, a magnitude 6¼ shock of intensity VIII in 1947 centered south of Virginia City in the southern part of Madison County, and a magnitude 7.1 shock of intensity X in 1959 centered near Hebgen Lake in the southern part of Gallatin County. The magnitude 6¾ shock near Lombard was felt strongly in Helena, where it caused minor damage and reached intensity VI. On the basis of this strong earthquake activity, a large part of west-central and southwestern Montana is included, along with parts of southeastern Idaho and western Utah, in zone 3 on the seismic zonation map in the Uniform Building Code (International Conference of Building Officials, 1976). Zone 3 includes areas in which earthquakes of intensity VIII or greater are expected to occur in the future.

Recently, a ground-acceleration probability map for the contiguous United States was prepared by Algermissen

FIGURE 9.—Ground crack in the floor of Helena Valley, about 3 km northeast of Lake Stanchfield, caused by the earthquake of 1935. Sand and water were forced from the crack as a result of liquefaction at shallow depth. Photograph courtesy of Montana Bureau of Mines and Geology.

and Perkins (1976, fig. 4). It gives an estimate of the maximum horizontal ground acceleration (expressed as a percent of gravity) to be expected that has a 90-percent probability of not being exceeded in 50 years. The accelerations are estimated for hard rock. On this map, the maximum expected horizontal ground acceleration indicated for the Helena area is 38 percent of gravity (0.38 *g*). That acceleration is more than three times the horizontal ground acceleration recorded in the basement of the Federal Building during the destructive aftershock of the Helena earthquake on October 31, 1935.

EARTHQUAKE HAZARDS

Earthquakes produce movements of the Earth's surface. These movements, which can damage manmade structures and the ground surface and result in fatalities, are called earthquake hazards. They include ground shaking, ground failure, and seiche and surge-induced flooding. The main characteristics and potential severity of these hazards are outlined in this section of the report.

A series of integrated earth-science studies published as U.S. Geological Survey Professional Paper 941-A (Borcherdt, 1975) comprehensively define the nature of earthquake hazards in the San Francisco Bay region of California. That publication is commended to readers who wish to gain a more detailed understanding of the complexities of the earthquake process and the diversity of earthquake effects than can be obtained from this summary report. The studies in Borcherdt (1975), which are widely applicable to other areas of high seismic risk, include papers on faults and future earthquakes (Wesson and others, 1975), estimation of bedrock motion at the ground surface (Page and others, 1975), differentiation of sedimentary deposits for purposes of seismic zonation (Lajoie and Helley, 1975), response of local geologic units to ground shaking (Borcherdt, Joyner, and others, 1975), liquefaction potential (Youd and others, 1975), landslides (Nilsen and Brabb, 1975), and predicted geologic effects of a postulated earthquake (Borcherdt, Brabb, and others, 1975).

GROUND SHAKING

Earthquake-generated ground shaking is the vertical and horizontal vibratory motion produced when seismic waves originate at a point of rupture on a fault surface and pass through the Earth's crust. This motion is extremely complicated and highly irregular, for it is the sum of many different harmonic oscillations of the ground, each with its own frequency and amplitude. In most instances it is the chief cause of damage during earthquakes and is the principal hazard associated with them. The intensity and nature of ground shaking largely depend upon earthquake source characteristics such as magnitude and size of fault rupture and upon distance from the source, but shaking also may be greatly influenced by surficial deposits and soils, by discontinuities in rock strata, and by geologic structure at the earthquake site.

RELATION TO MAGNITUDE AND DISTANCE

The intensity of earthquake ground shaking generally increases with earthquake magnitude and decreases with distance away from the earthquake source. These relations are indicated by the enlargement of the area of intense shaking and the enlargement of the area over

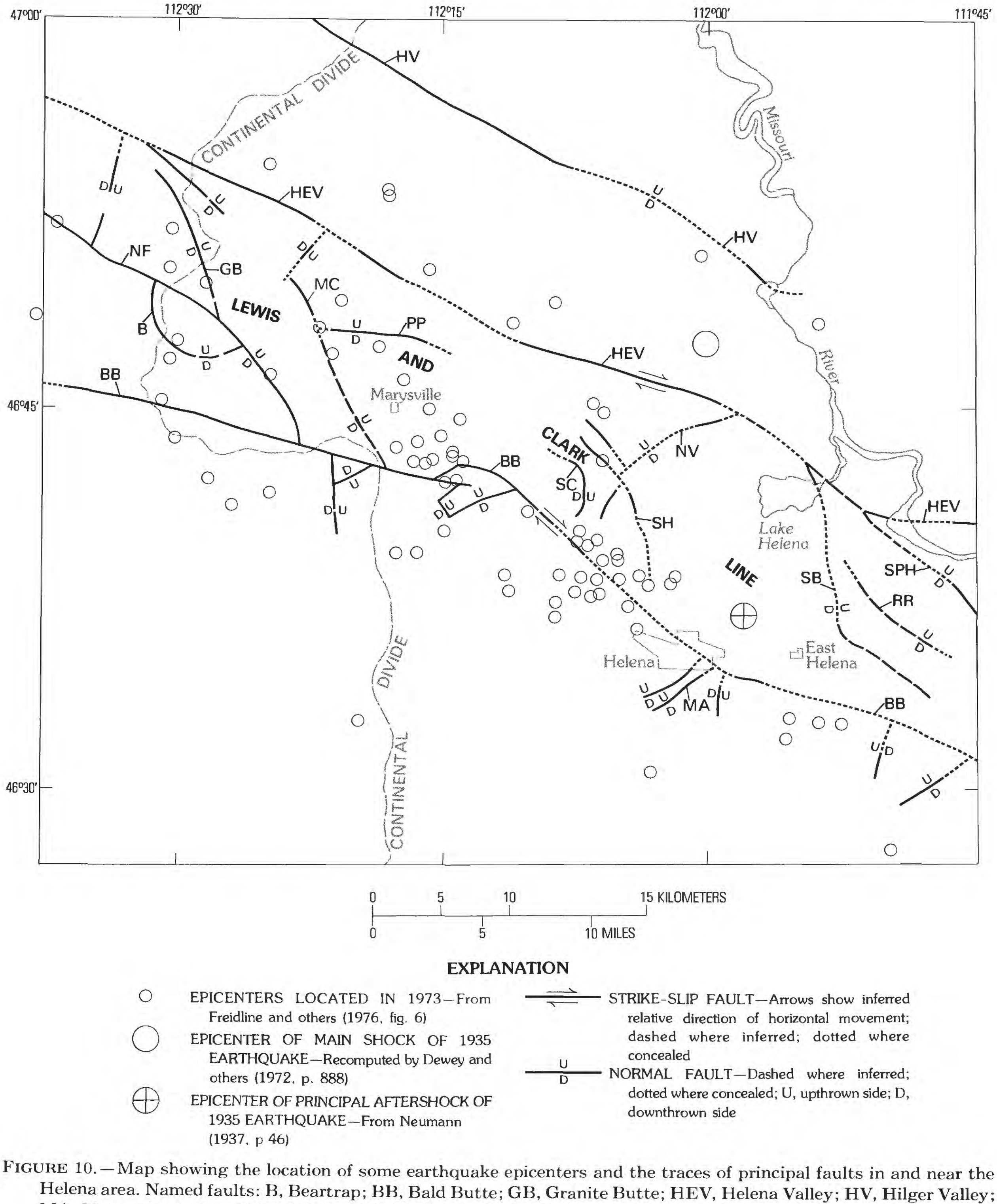


FIGURE 10.—Map showing the location of some earthquake epicenters and the traces of principal faults in and near the Helena area. Named faults: B, Beartrap; BB, Bald Butte; GB, Granite Butte; HEV, Helena Valley; HV, Hilger Valley; MA, Mount Ascension; MC, Marsh Creek; NF, North Fork; NV, Northwest valley; PP, Prickly Pear; RR, Regulating Reservoir; SB, Spokane Bench; SC, Silver Creek; SH, Scratchgravel Hills; SPH, Spokane Hills.

which earthquakes are felt as magnitude increases and by the progressive lessening of earthquake effects, such as damage, away from the source. A detailed study of intensity variation as a function of source distance for different earthquake magnitudes was made by Barosh (1969, p. 16-24).

The increase in intensity with magnitude is also apparent in the way in which ground motion is perceived by people in the source region of an earthquake. Small to moderate earthquakes (those with magnitude less than 5.0) are usually felt as a sudden tremor or sharp jolt that lasts for a second or less. Strong earthquakes (those with magnitude between 5.0 and 6.9) produce vibrations of much greater amplitude, and the shaking is felt as an intense jolting, rocking, or rolling motion that lasts for several seconds, followed by weaker tremors that may continue for as much as a minute. Major earthquakes (those with magnitude between 7.0 and 7.9) and great earthquakes (those with magnitude 8.0 or more) generate motion that is characterized by oscillations of very large amplitude, and the shaking is perceived as a violent tossing and lurching of the ground that may last for many seconds, followed by progressively weaker tremors that may continue for as much as several minutes.

As a rule, the intensity of earthquake ground shaking decreases rapidly near the earthquake source and then more and more slowly as the distance increases. However, this decline in intensity usually varies with direction away from the source, and so isoseismal lines are rarely circular and either show an elliptical elongation in the direction of some major structural trend or are irregular. For example, the isoseismal map of the main shock of the Helena earthquake of 1935 (fig. 5) shows a weak but decided elongation parallel to the main structural grain of the Rocky Mountains. Locally, the pattern of shaking is strongly influenced by the distribution of surficial deposits at an earthquake site because ground motion is intensified in these materials. Consequently, isolated areas of intense shaking may occur on soft ground far from the earthquake source. The size of the fault rupture that produces an earthquake also may greatly affect the distance-intensity relations of ground shaking. If the fault breakage extends to the surface, heavy shaking is generally concentrated in a narrow region along the length of the ruptured fault, and isoseismal lines are highly elongated parallel to the fault trace.

AMPLIFIED SHAKING ON SURFICIAL DEPOSITS

Earthquake intensity has been reported to be greater on unconsolidated surficial deposits than on nearby bedrock in many earthquakes. This relation is probably due, at least in part, to amplification of the ground motion in the surficial materials, particularly for longer period motion. It may also be due in part to increased duration of shaking on such materials. Other effects of the surficial deposits are perhaps to lengthen the period of the dominant vibrations and to increase the degree of periodicity in the motion.

Quantitative data on ground-motion amplification in surficial deposits were obtained by Gutenberg (1957) in a study carried out in southern California in which the shaking characteristics of small, natural earthquakes in areas of alluvium (surficial deposits) were compared to the ground motion of the same earthquakes on crystalline bedrock. In that study it was found that, for ground vibrations having periods of 1-1½ s (long-period oscillations), the ratio of amplitudes at localities on fairly dry alluvium more than 500 ft (152 m) thick to amplitudes on bedrock was as much as 5:1 and ranged to as much as 10:1 on water-saturated ground; and it was further observed that vibrations with periods of about ¼ s produced relatively heavy shaking in areas with a cover of alluvium only about 100 ft (30 m) thick (Gutenberg, 1957, p. 238). Perhaps even more significant than the amplification effects were the results concerning the duration of ground motion, which showed that relatively strong shaking on alluvium lasted several times longer than on crystalline bedrock and that shaking on deep alluvium lasted longer than on thin alluvium (Gutenberg, 1957, p. 235).

Investigations in the San Francisco Bay region of California (Borcherdt, 1970; Borcherdt, Joyner, and others, 1975) have demonstrated that certain frequencies of ground shaking at low-strain levels are substantially amplified in some surficial geologic units. For example, recordings of low-intensity motions in that area produced by nuclear testing at the Nevada Test Site showed that horizontal ground velocities were five to eight times greater on the surface of bay mud than on nearby bedrock (Borcherdt, 1970, p. 35; Borcherdt, Joyner, and others, 1975, p. A56).

Probably the ground-motion amplitudes measured for small earthquakes cannot be linearly extrapolated to the much stronger motions that are associated with destructive earthquakes. Furthermore, the few comparative measurements of stronger motion that are available are insufficient to draw meaningful conclusions about the shaking behavior of surficial geologic units at high-strain levels. However, the distribution of Mercalli intensity for some earthquakes suggests that some high-intensity motion produced by large shocks is greatly magnified in surficial deposits, particularly longer period motion that is close to the fundamental vibrational frequency of the materials. In addition, strong-motion data obtained during the magnitude 6.5 earthquake at San Fernando, California, in 1971 appear to indicate that certain parameters of high-strain motion may be significantly amplified in soils or surficial deposits.

Evidence of strongly amplified shaking in unconsolidated surficial materials has been documented for several large earthquakes. For example, Duke and Leeds (1959) noted in a study of the magnitude 7.5 Mexico earthquake of July 28, 1957, that the intensity of ground shaking in Mexico City, about 250 km from the earthquake source and founded on deep alluvium of ancient Lake Texcoco, was much greater than at localities situated about 100 km from the source and founded on firmer deposits or on granite bedrock. The increased intensity at Mexico City, which contributed to extensive damage to taller structures, was attributed mainly to enhanced long-period vibratory motion in the Lake Texcoco deposits. Similar ground-motion effects at Mexico City were induced by distant, strong earthquakes in 1962 (Zeevaert, 1964) and in 1978. Much of the heavy damage to buildings during the magnitude 6.4 Caracas, Venezuela, earthquake of July 29, 1967, also has been ascribed to destructive resonance effects that accompanied amplified shaking of surficial deposits in Caracas Valley (Seed and others, 1972, p. 787-806). Other earthquakes for which there is substantial evidence that damage to buildings was directly related to intensified shaking on underlying surficial materials are the magnitude 8.3 San Francisco, California, earthquake of 1906 (Wood, 1908) and the magnitude 5.6 and 5.7 Santa Rosa, California, earthquakes of 1969 (Miller, 1970).

Boore and others (1978, p. 17-18) compared strong-motion data recorded on rock (bedrock) and soil (surficial deposit) sites during the 1971 San Fernando, California, earthquake over a distance range of 15-100 km. Their analysis showed that peak horizontal ground acceleration was not significantly different on the bedrock and soil sites, whereas peak horizontal ground velocity and peak horizontal ground displacement were significantly greater on the soil sites. Accordingly, they "tentatively conclude that amplification of velocity and displacement is a real effect associated with soil sites." The precise nature of the amplification mechanisms in the soils is unknown.

SHAKING AND DAMAGE

Almost all structures—single-family dwellings, high-rise buildings, powerplants, bridges, dams, smoke stacks, water towers, and other structures—are subject in some degree to damage from ground shaking during an earthquake. This damage is potentially hazardous to human beings, can be very costly to repair, and, if extensive, can affect the functioning of an entire community. In general, the degree of damage imparted to a structure by ground shaking depends to a large extent on its original engineering design; consequently, earthquake provisions are incorporated into building codes in many seismically active areas of the world. In the absence of proper engineering precautions, damage from large earthquakes can be almost total. The destruction of the high school at Helena on October 31, 1935, is an example (fig. 6).

Most of the damage produced by earthquake ground shaking is caused by forces resulting from the horizontal component of motion, which is essentially unresisted by gravity. Provision against lateral forces is therefore of utmost importance in the design of buildings and other structures to make them earthquake resistive (Seismology Committee, Structural Engineers Association of California, 1975, p.1C-3C). All engineering structures are designed to resist the vertical force of gravity and are thus generally capable of supporting the additional vertical load of an earthquake. Only in great earthquakes, in which vertical displacement of the ground may reach many centimeters and in which accelerations may approach or even exceed the acceleration of gravity, is a vertical seismic overload likely to cause failure.

Damage from earthquakes is closely dependent upon dynamic characteristics of the ground motion such as acceleration, velocity, displacement, duration, and frequency or wave-period content. The acceleration, velocity, and displacement of the earth motion are indicative of the force that is applied to the ground and to structures during shaking; duration is responsible for certain types of failure that are time-dependent and that result from long-continued vibrational stress; and frequency content governs amplification and resonance effects in unconsolidated deposits. These parameters are important in earthquake engineering and in seismic hazards assessment, where quantitative estimates of ground shaking are necessary for design purposes and site evaluation. Only a few general observations concerning the influence of these factors on damage are given here.

The acceleration, velocity, and displacement of earthquake ground motion generally define the magnitude of the stresses and strains that the Earth's surface and structures undergo during an earthquake. Acceleration is directly related to the force induced on structures and thus to their structural response during shaking; velocity determines input energy and thus tends to correlate with the severity of damage; and displacement is a measure of the strain induced by the motion and is responsible for damage resulting from excessive deformation. As a rule, acceleration, velocity, and displacement increase with earthquake magnitude at any given point from the earthquake source and decrease with distance away from the source, but the rate of decrease is somewhat less for velocity and displacement than for acceleration. In general, damage tends to increase as acceleration, velocity, and displacement increase, but this relation is complicated because of the variable response of surficial deposits and manmade structures to strong ground motions.

Some representative values for horizontal acceleration, velocity, and displacement obtained from accelerograms for several earthquakes in the magnitude range 5.3-7.2 are listed in table 1.

Strong-motion records from the source region of earthquakes of magnitude greater than 6.0 are scarce. Data

TABLE 1.—*Selected strong-motion data for several earthquakes in the magnitude range 5.3-7.2*

[From Boore and others, 1978, p. 33-40]

Earthquake	Magnitude	Site	Distance[1] (km)	Horizontal acceleration (g)	Horizontal velocity (cm/s)	Horizontal displacement (cm)	Duration[2] (s)
Daly City, Calif., 1971	5.3	Rock	8.0	0.127	4.9	2.3	1.6
Parkfield, Calif., 1966	5.5	Soil	6.6	0.509	78.1	26.4	12.1
Oroville, Calif., 1975	5.7	Rock	8.0	0.110	5.0	1.6	0.0
Imperial Valley, Calif., 1940	6.4	Soil	12.0	0.359	36.9	19.8	29.3
San Fernando, Calif., 1971	6.4	Rock	3.2	[3]1.251	113.2	37.7	13.3
Puget Sound, Wash., 1949	7.1	Soil	48.0	0.306	21.4	10.4	22.3
Kern County, Calif., 1952	7.2	Soil	42.0	0.196	17.7	9.1	19.6

[1]Shortest distance in kilometers to the surface of fault slippage.
[2]Time interval between first and last acceleration peaks equal to or greater than 0.05 *g*.
[3]Highest ever measured.

have been obtained only in the magnitude 6.5 San Fernando, California, earthquake of 1971 and the magnitude 6.4 Imperial Valley, California-Mexico, earthquake of 1979. On the basis of considerations that allow for the effects of surface topography on the peak acceleration of 1.25 *g*, on the peak velocity of 113 cm/s, and on the peak displacement of 38 cm recorded at a distance of 3 km from the causative fault during the 1971 San Fernando earthquake (see table 1), Boore and others (1978, p. 25) concluded that "it is difficult to accept estimates less than about 0.8 *g*, 110 cm/s, and 40 cm, respectively, for the mean values of peak acceleration, velocity, and displacement at rock sites within 5 km of fault rupture in a magnitude 6.5 earthquake." Significantly, those estimates generally appear to be substantiated by preliminary strong-motion records obtained close to the source of the 1979 Imperial Valley earthquake (Porcella and Matthiesen, 1979, table B). Substantially higher values of acceleration, velocity, and displacement may be reached in the source area of larger shocks. For example, Page and others (1972, table 2) estimated that the values for maximum horizontal ground acceleration, velocity, and displacement, respectively, may reach 1.25 *g*, 150 cm/s, and 100 cm within a distance of a few (3-5) kilometers of a causative fault in a magnitude 8.5 earthquake.

The duration of ground shaking is an important factor in producing damage in large earthquakes, for failure in manmade structures and the initiation of certain types of ground failure are time dependent and result from a progressive weakening as earth vibration continues. The critical factor in severe earthquake damage is the number of stress pulses imparted by the ground motion at potentially damaging levels of acceleration, velocity, and displacement. Accordingly, the incidence and degree of failure tend to become greater as the duration of shaking increases. An excellent example of the duration effect is provided by the Helena earthquake of 1935 in which many structures weakened by the main shock on October 18 were subsequently badly damaged or collapsed by the strong aftershock that followed on October 31.

The duration of strong ground shaking is commonly defined as the interval of shaking above a threshold acceleration value of 0.05 *g* recorded by a strong-motion accelerograph, or, stated somewhat differently, the interval on an accelerogram between the first and last acceleration peaks that have a value equal to or greater than 0.05 *g*. Duration so defined is called the "bracketed duration" of an earthquake. It increases with magnitude and decreases at a fairly rapid rate away from the earthquake source due to attenuation of the ground motion. The bracketed durations for some earthquakes in the magnitude range 5.3-7.2 are listed in table 1. Much higher values may be reached in the source region of larger shocks.

The frequency content of earthquake ground motion is a vital factor in earthquake damage consideration. As previously noted, the amplification of ground shaking on surficial deposits is strongly dependent on frequency. In addition, resonance of surficial deposits and of manmade structures during earthquakes, which can be highly destructive, is directly related to frequency content.

Resonance effects can occur in surficial materials or in structures if the fundamental vibrational frequency of the deposits or of the structures is close to frequencies contained in earthquake ground motion. Damaging oscillations caused by resonance are most likely to occur in a structure whose fundamental frequency coincides with that of the ground, for in that circumstance the effects of site resonance and structural resonance are additive. Accordingly, taller buildings may be stimulated into dangerous oscillation on thick accumulations of surficial deposits, whereas lower structures may respond with damaging oscillation on thinner bodies of unconsolidated materials or even on firm ground. Resonance of the ground and of structures during earthquakes is one of the main reasons that damage increases with magnitude, for the stronger shocks produce a greater range of vibration frequencies that may coincide with the fundamental frequencies of buildings and the supporting ground. In California, a site factor is usually included in seismic design calculations to account for resonance effects (Seismology Committee, Structural Engineers Association of California, 1975, p. 26C-28C).

GROUND FAILURE

Large earthquakes commonly produce secondary effects that involve sudden, permanent failure of the ground surface. The most common types of failure are landsliding, liquefaction-induced failure, surface faulting, regional land displacement, settlement, ground cracking, ridging and furrowing, and ground churning. Any one of these effects can be damaging, even catastrophic, and an understanding of their physical nature and of how and where they may originate is important in efforts to reduce earthquake hazards.

The degree to which ground failure takes place during an earthquake generally correlates with the intensity and duration of ground shaking and with the extent of geologic features and materials at the earthquake site that are prone to failure. In Montana, ground failure was extensive in, for example, the Lombard earthquake of 1925 (Pardee, 1927, p. 8-10) and in the Hebgen Lake earthquake of 1959 (Hadley, 1964; Witkind, 1964a, 1964b).

LANDSLIDING

Landslides are produced by natural movement of rock and soil down slopes. They form in all types of rock materials and from many different causes, and they move by many mechanisms. In scale, they range from individual blocks of rock that tumble down steep slopes, through small earth slumps a few tens of meters across, to avalanches of rock that may travel several kilometers and involve millions of cubic meters of material.

Strong earthquakes can effectively increase the forces acting to cause failure on slopes. Earthquake ground motion thus commonly triggers landsliding, chiefly on steep, marginally stable slopes where the downslope component of the force of gravity is high. Seismically induced landslides have caused great damage, numerous fatalities, and extensive disruption of travel in many parts of the world. A classic example was the catastrophic rock slide that plunged into the canyon of the Madison River during the major earthquake at Hebgen Lake, Montana, in 1959 (Hadley, 1964, fig. 54). In addition to obviously causing landslides associated with the period of shaking, earthquake ground shaking also may loosen and weaken deposits on slopes so much that another event may trigger a slide failure weeks or even months after the earthquake disturbance has ceased. The landslide hazard associated with earthquakes therefore may persist long after the main seismic event.

The enormous damage that earthquake-caused landsliding may inflict is well illustrated by landslip effects that occurred during the great Indian (Assam) earthquake of 1897 (magnitude 8.7). In that earthquake, as described by Oldham (1899, p. 111-123), high, steep bedrock slopes in the hills in the area of major shaking were stripped bare of vegetation, soil, and loose rock, all of which plunged into the bottom of valleys and choked them with huge masses of debris. Significantly, considering slopes of comparable height and steepness, the landsliding was notably more severe in terrain underlain by sedimentary bedrock (sandstone and limestone) than in terrain formed of granitic (plutonic) and crystalline metamorphic rocks.

Landslides can be described by the mechanisms that move them, by the type of material in which they develop, by their velocity, and by their displacement. Keefer (1984) studied 40 historical earthquakes and identified 14 types of landslides "caused by seismic events" (p. 420). Several common or representative landslide mechanisms that can operate during earthquakes to produce slides are slump or rotational slip, earthflow, and rockfall. Earth lurching, a type of movement characteristically associated with earthquakes, also can produce slides in rock and unconsolidated material. Landslides produced by mechanisms like these are sketched in figure 11 and briefly described in the following paragraphs. Special kinds of landslides associated with liquefaction during earthquakes are discussed in the next section of the report.

Slump and rotational slip (fig. 11*A*) are common slide-producing processes. Slumps generally form on steep to moderate slopes in surficial deposits or other soft earth materials and are a common feature at the sides of valleys, along stream embankments, and in deep roadcuts. Slumping ordinarily begins along a horseshoe-shaped fracture in the ground that curves beneath the slide mass; downward and outward rotational slip along this surface moves the slide. Commonly, steep transverse cracks form, which curve downward toward the front of the moving mass and may merge with the basal slide surface. Slumping can occur suddenly and rapidly, but more commonly it occurs gradually and the slide moves very slowly.

Earthflows (fig. 11*B*) are not as common as slumps, but usually they are longer and cover a much larger area. They form on gentle, moderate, or steep slopes and generally originate in moist or water-saturated surficial deposits, soils, or other loose earth material, although some are formed in fragmented bedrock. In this type of slide, the boundary between the moving mass and the underlying stable rock is not a well-defined slip plane but instead is a transition zone in which movement gradually diminishes with depth. In a true earthflow, the entire sliding mass is mobilized as a viscous fluid that

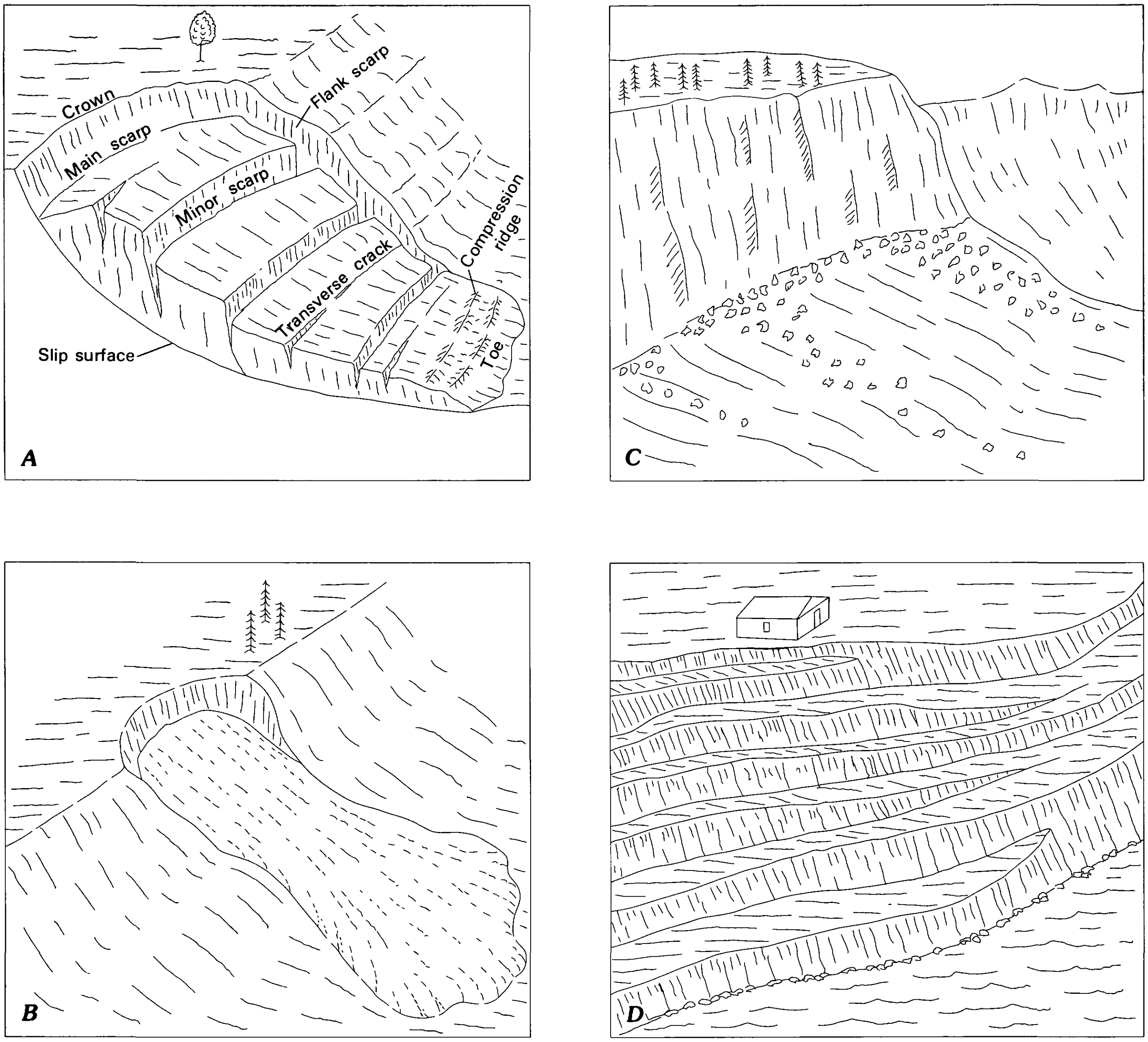


FIGURE 11.—Types of landslides classified according to their mechanism of movement. *A*, slump or rotational slip; *B*, earth flow; *C*, rockfall; *D*, slide caused by earth lurching.

flows downslope; the velocity and displacement of the material are greatest at the surface of the mass and least at the base. Most earthflows move very slowly by the process referred to as creep, and they may move long distances if the slope characteristics are favorable. Some earthflows, composed of solid bedrock fragments, actually resemble glaciers, where the flowing mass is fed by spalling off of rock at a headward scarp that continually supplies new material to the flow. These slides, which commonly contain water or ice in void spaces, usually form in steep, mountainous terrain.

Rockfalls (fig. 11*C*) are a common slide process on steep slopes formed of brittle bedrock, and Keefer (1984, table 4) listed rockfalls and rock slides as "very abundant" (his most abundant class) among earthquake-induced landslides. In such slides, the moving rock mass falls, rolls, bounces, or slips down a slope—generally rapidly—and has little or no coherent contact with the underlying stationary base. Rockfalls are of short lateral extent, although they may move considerable distances vertically (as when rocks are dislodged from high cliffs), and if they fall into a river or lake, their influence may travel far. Because they are largely confined to mountainous areas, damage caused by rockfalls may often be minimal, but when they cause damage—directly or indirectly—it can be severe.

Earth lurching (fig. 11*D*) is characteristically associated with earthquakes. Earth lurching can produce a peculiar wedging apart of surficial deposits or other soft earth materials by back-and-forth earthquake motion; slides due to lurching can take place at right angles to the margin of steep slopes such as are found along bluffs, streambanks, lakeshores, and artificial road and railway embankments. Such slides result from yielding of ground toward the unsupported face of a slope. First, a series of nearly parallel cracks or fissures form, separating the ground into rough blocks; as shaking continues, the outer block at the slope margin slides down as an intact mass. Successive slumping of other blocks can produce a slump form resembling a flight of stairs. Minor sliding of this sort may occur along banks and bluffs in strong earthquakes, but extensive sliding due to lurching is associated with shocks of magnitude 8.0 or more in which the duration of strong shaking may be several-score seconds. In the magnitude 8.4 Bihar-Nepal (Indian) earthquake of 1934, earth lurching and the resulting landforms were especially common along lake shores, riverbanks, and embankments of artificial fill, and, in numerous instances, road and railway foundations as much as 2 and 3 m high were quickly reduced to the level of the surrounding country by the lurching process (Dunn and others, 1939, p. 38-39). Somewhat similar lurching occurred on water-saturated level ground in the Muzaffarpur district during the Bihar-Nepal earthquake (Ghosh, 1939).

The presence of slope is a prerequisite of all landslides, for a tangential component of the force of gravity parallel to the surface of a sliding mass is necessary for movement to occur. In simple mechanical terms, landslides result when the downslope component of the force acting on a rock mass exceeds the shearing strength of the material and causes it to separate from adjoining stationary rock and to move downward under the influence of gravity. A slide therefore implies either that the force acting on the material was increased or that the shearing resistance of the material was lowered, and, because both of these conditions may be induced by ground shaking, landsliding is common during earthquakes. Under normal conditions, most landslides result either from oversteepening of slopes by erosion or by man's activities, which increases the downslope component of force, or from a decrease in strength of the slope materials caused by heavy rainfall, removal of vegetation, or weathering.

Many complex factors control the stability of slopes and their susceptibility to landsliding. Steepness is a primary factor—the larger the angle of slope, the greater the downslope component of gravity acting upon underlying soil or rock. Landslides are therefore more abundant on steep slopes than on gentle slopes. For example, in the San Francisco Bay region of California, it was determined that landslides are common on slopes of more than 15 percent, few on slopes of 5 to 15 percent, and virtually absent on slopes of less than 5 percent (Nilsen and Brabb, 1975, p. A81). Landslide susceptibility is also controlled by the types of rock or soil that underlie slopes and by the structural characteristics of the slope materials. In general, landslides are more abundant in thick soils, surficial deposits, and soft sedimentary rocks such as clay and shale, but the largest slides occur in bedrock. Structures in rocks such as joints, fissures, bedding planes, and faults, and the orientation of these features with respect to slopes, can affect slope stability and the potential for landsliding. A particularly hazardous feature is the orientation of bedding planes parallel or nearly parallel to the slope of hillsides. The stability of slopes is also influenced by moisture content. The addition of water to surface rocks and soils lowers their resistance to sliding by increasing load weight, establishing pore-water pressure and dissolving mineral cement. The incidence of landsliding is therefore greatest in regions of wet climate. Other factors that affect slope stability are the amount and kind of vegetative cover; the degree to which slopes are steepened or undercut by erosion; and the extent of land modifications produced by man. Because the susceptibility of slopes to landsliding depends on so many variables, about which exact data are usually lacking, evaluation of regional landslide potential is generally imprecise.

The incidence of landsliding tends to increase as earthquake magnitude increases. The shocks of magnitude 6 and 6¼ in the Helena, Montana, earthquake of 1935 produced only minor landsliding in the form of a few rockfalls in the surrounding mountains and a small slump that covered part of U.S. Highway 91 in the valley of Prickly Pear Creek about 11 km south of Helena (Scott, 1936, p. 13). Landsliding was much more prevalent in the magnitude 6¾ Lombard, Montana, earthquake of 1925. It produced numerous rockfalls and small slides on steep slopes and cliffs and one large slide, estimated at about 30,000 m^3, that blocked the valley of Sixteenmile Creek and covered the railroad near Deer Park (Pardee, 1927, p. 8-10). The slides in the 1925 earthquake were most numerous within 20-24 km of the epicenter, but some rockfalls occurred as far as 65 km away (Pardee, 1927, p. 9). The magnitude 7.1 Hebgen Lake, Montana, earthquake of 1959 triggered extensive landsliding, ranging from innumerable small rockfalls and slumps, through large slides down steep slopes, to the massive avalanche of some 30.5 million m^3 of bedrock and loose slope debris that slid into the canyon of the Madison River below Hebgen Lake (Hadley, 1964, p. 107-121). All of the fatalities (28) incurred from the Hebgen earthquake were a direct result of landsliding. Timber and road damage caused mainly by slide processes exceeded $11,000,000 (Coffman and von Hake, 1973, p. 73). Major landsliding during the Hebgen quake was concentrated in a 2,600-km^2 area around the earthquake epicenter, but many smaller landslides and rockfalls occurred far outside this region, particularly in the northern part of Yellowstone National Park and in the canyon of the Yellowstone River near Gardiner, Montana (Hadley, 1964, p. 122-123).

LIQUEFACTION-INDUCED FAILURE

Earthquake-generated liquefaction may be defined as the process whereby consolidated water-saturated sediments are transformed into a fluid state as a result of build-up of hydrostatic pressure between the sediment grains. Silts and fine-grained sands are the sediments most susceptible to liquefaction, but the process also can occur in coarser materials and even in gravel. Liquefaction has been recognized as the underlying cause of many catastrophic landslides and of other types of destructive ground failure during earthquakes, and a renewed focus on the problem in recent years has greatly advanced our understanding of the mechanical principles that govern the process and the types of ground failure that are associated with it (Youd, 1973).

Liquefaction occurs when earthquake vibrations cause the grains in a layer of water-saturated sediment to rearrange themselves into a more compact state. As grain reorientation takes place, grain-to-grain load stress is temporarily reduced, and part of the stress is transferred to the water that occupies the pores between the grains. This transfer of stress causes an increase in the hydrostatic pressure, which, in turn, reduces the shear strength of the sediment. If the hydrostatic pressure reaches a value equal to the confining pressure (the pressure exerted by the weight of overlying deposits), the sediment may transform into a viscous liquid and begin to flow. Other effects commonly occur in conjunction with the liquefaction. When the ground vibrations cease, reconsolidation of the liquefied layer may cause pore water to move into overlying sediments, and this process may culminate in the ejection of water and sediment at the surface in the form of sand boils or fountains, or even in a general condition of water seepage that leads to flooding of the ground surface. The overall degree to which liquefaction takes place in an earthquake depends upon the extent of sediment cover susceptible to the process and upon the intensity and duration of ground shaking in the affected area. Liquefaction itself does not present a serious problem during earthquakes unless it leads to movement or settling or flooding of the land surface.

Ground dislocation associated with liquefaction may be grouped into three basic categories on the basis of the mechanics of the failure process: flow landslides, lateral-spreading landslides, and quick-condition failures (Youd, 1973; Youd and others, 1975). Flow landslides result when masses of loose granular sediment at and near the ground surface are liquefied and slope conditions permit a large amount of unrestrained flow. They generally form on moderate to steep slopes as liquefied flows or as slides composed of large, discrete blocks of cohesive sediment riding on liquefied flows (Youd, 1973, p. 7). Such slides may move long distances (as much as a kilometer or more) and cover wide areas of the land surface; they are by far the most damaging type of slide caused by liquefaction. Lateral-spreading landslides result when layers of loose to moderately dense material become liquefied at shallow depth and movement is restricted to distances of a few tens of meters or less. These slides usually form on gentle slopes as slow-moving masses that spread laterally, and their surfaces commonly undergo cracking and differential settlement, especially at the margins (Youd and others, 1975, p. A72). Such slides can be very damaging to structures located on or in the moving mass. Quick-condition failures generally result when pore water in a liquefied layer rises into overlying near-surface sediments and they reach a condition resembling quicksand. This type of failure usually occurs in flat-lying areas underlain by sediments of considerable thickness where the water table is close to the surface (Youd and others, 1975, p. A73). Damage in quick-condition failures can be very extensive owing to the settlement of structures into the soil or to the buoyant rise of buried structures, such as fuel tanks, through the liquefied sediment.

The following examples illustrate the extreme destructiveness that has resulted from various types of liquefaction-induced ground failure in some earthquakes of large magnitude.

In Kansu Province, China, a large part of the land surface is formed by thick deposits of wind-laid silt called loess. A major earthquake in that area on December 16, 1920, triggered great flow landslides in the loess, some of which moved at a relatively high velocity for distances of more than a kilometer. An estimated 200,000 people, including many that lived in excavations carved into the loess, perished in the slides. The Kansu landslides, and similar landslides triggered by an earthquake near Hsian in Shensi Province in 1556 in which almost a million people are believed to have died, were apparently caused by spontaneous liquefaction of the loess, but the exact mechanism of failure is unknown. The entrapment of air in the slides, especially at their base, may have greatly facilitated long-distance movement of the material (Bolt and others, 1975, p. 187).

At Anchorage, Alaska, in the magnitude 8.4 earthquake of March 27, 1964, an area extending about 2.5 km along the coast and reaching inland as much as half a kilometer slid toward the ocean (Knik Arm), as a huge lateral-spreading landslide. This slide caused great damage to a residential area called Turnagain Heights, where some of the slide blocks moved as much as 300 m and houses actually slid into the chasms between them. That landslide has been attributed to liquefaction of thin layers of sand and silt in a near-surface clay (Hansen, 1965, p. A65).

One of the most spectacular quick-condition failures of modern times took place in Niigata, Japan, during a magnitude 7.5 earthquake on June 16, 1964, when sandy soil on which much of the city was built became liquefied and hundreds of buildings settled into the ground (Seed and Idriss, 1967, p. 83). Some structures, including several large apartment buildings, settled more than 3 feet (1 m), and one of the apartment buildings tipped and rotated through an angle of 80°.

SURFACE FAULTING

Sudden rupture and displacement of the ground surface along faults has occurred in many parts of the world during earthquakes. These displacements usually result from translation of the quake-generating rupture to the ground surface along a causative fault or from reactivation of faults by strong ground motion. Large-scale surface faulting is typically limited to strong earthquakes, usually of magnitude greater than 6.5, but significant surface offsets have occurred during shocks of magnitude 6.0-6.5 and even in smaller shocks whose magnitudes were less than 5.5 (Bolt and others, 1975, p. 33-46). Large-scale surface fault rupture took place in the magnitude 7.1 Hebgen Lake, Montana, earthquake of 1959. It is not known if surface faulting occurred in any of the other destructive shocks that have shaken Montana.

The surface displacement and length of rupture that occurred along faults in several historic earthquakes are presented here to illustrate the degree of breakage that may take place on different types of faults at a wide range of earthquake magnitudes. During the magnitude 8.3 San Francisco earthquake of 1906, the horizontal slip on the San Andreas fault was as much as 5 m and breakage extended over a length of about 430 km (Wesson and others, 1975, p. A13, A38). The series of earthquakes that reached a magnitude of 5.5 in the Parkfield-Cholame area of California in 1966 produced a horizontal slip of a few centimeters along a 37.8-km segment of the San Andreas fault (Brown and Vedder, 1967, p. 11). Vertical displacement of more than 14 m—the greatest known—occurred on submarine faults during the magnitude 8.6 Cape Yakutat, Alaska, earthquake of 1899 and the magnitude 8.4 Alaskan earthquake of 1964, but the length of rupture on those fractures is unknown (Coffman and von Hake, 1973, p. 106-109). In the magnitude 8.7 Indian (Assam) earthquake of 1897 (Oldham, 1899, p. 138-152), vertical displacement was as much as 10.7 m and the rupture length was about 19.3 km along the Chedrang fault, and lesser faults underwent a vertical movement of as much as 3 m and had rupture lengths of as much as 11.3 km. In the Hebgen Lake, Montana, earthquake of 1959, vertical displacement was as much as 4.3 m and the rupture length was about 22.5 km on the Red Canyon fault, and vertical displacement was as much as 6 m and the rupture length was about 12 km on the Hebgen fault (Witkind, 1964b, p. 37). The magnitude 6.5 San Fernando, California, earthquake of 1971 produced a thrust or reverse displacement of about 1 m along a 15-km segment of the San Fernando fault zone at the foot of the San Gabriel Mountains (U.S. Geological Survey, 1971, p. 55).

Surface fault ruptures may consist of a single, narrow main break, but, commonly, subsidiary branch and secondary faults are formed on either side of the main fracture and the rupture forms a zone of disturbance of varying width. The principal displacement usually occurs along the main fault trace, but offsets on subsidiary faults, even at considerable distance from the main break, can be substantial and amount to as much as a meter or more. The degree of displacement and the width of the zone of deformation along surface ruptures generally increase with earthquake magnitude, and Bonilla (1970, p. 56) determined that zone width also varies with the type of faulting; it is narrowest for strike-slip faults and widest for normal and reverse faults at roughly equivalent levels of earthquake magnitude. Moreover, the rupture zones along reverse faults generally appear to be more complex and more irregular than those formed along normal or strike-slip faults (Wesson and others, 1975, p. A25). Some representative maximum fault-zone widths formed along earthquake-induced surface breaks in the United States are 100 m on the San Andreas strike-slip fault during the magnitude 8.3 San Francisco earthquake of 1906 (Lawson, 1908, p. 53), 60 m on the reactivated normal faults at Hebgen Lake during the magnitude 7.1 Montana earthquake of 1959 (Witkind, 1964b, p. 46), and 200 m on the reverse-fault rupture during the magnitude 6.5 San Fernando, California, earthquake of 1971 (U.S. Geological Survey, 1971, p. 57).

Although surface faulting is one of the most spectacular effects of earthquakes, damage to manmade structure and the land surface and fatality resulting from the process are usually small compared to that resulting from ground shaking or landsliding because fault movement is ordinarily confined to a fairly narrow zone alone the slipped fault trace. It is obvious, however, that a fault displacement of even a few centimeters beneath or across a structure may result in extensive damage, especially if the fault movement is accompanied by intense ground shaking. Severe damage to several buildings astride the Hebgen fault occurred during the Hebgen Lake, Montana, earthquake of 1959 (Witkind, 1964b, fig. 26). Ground rupture along the San Fernando fault zone during the San Fernando, California, earthquake of 1971 caused severe damage to buildings, broke gas and water mains, and damaged roads (Lew and others, 1971, p. 25-26; Nichols and Buchanan-Banks, 1974, fig. 1). The Parkfield-Cholame, California, earthquake of 1966 caused ground fracturing that bent and cracked bridges, roads, fences, pipelines, a concrete canal, and a small earth-fill dam (Brown and Vedder, 1967, p. 22).

REGIONAL LAND DISPLACEMENT

Earthquake-induced surface faulting may result in sudden ground displacement that involves subsidence, uplift, and horizontal shifts of wide areas of the Earth's surface. These displacements range from a few centimeters or less to many meters and may affect thousands of square kilometers of the land surface.

The largest documented land displacement was that caused by the Alaskan earthquake of 1964, during which more than 250,000 km^2 of the Earth's surface in south-central Alaska was measurably displaced by crustal deformation that included a maximum uplift of 11.6 m, a maximum subsidence of 2.3 m, and a maximum seaward horizontal shift of 19.5 m (Eckel, 1970, p. 11). In the conterminous United States, the most extensive changes in land level caused by an earthquake were those that occurred during a series of three powerful shocks centered near New Madrid, Missouri, in 1811 and 1812. In those earthquakes, great blocks of land were raised and lowered as much as 3-4 m within an area of some 130,000 km^2; as a result, new lakes formed and extensive changes in the drainage pattern occurred (Coffman and von Hake, 1973, p. 43-46). At Hebgen Lake, Montana, widespread subsidence and warping of the land surface accompanied the reactivation of surface faults in the earthquake of 1959. The main dislocation covered a tract about 60 km long and about 22½ km wide, and within that area about 155 km^2 of the land surface that included Hebgen Lake dropped more than 3 m and the maximum subsidence was about 6.7 m (Myers and Hamilton, 1964, p. 55).

Regional land displacement that involves vertical movement of the Earth's surface usually has a profound effect upon surface waters, and damage connected with this type of dislocation is mostly caused by sudden movements of water, changes in water level, and changes in drainage pattern. A spectacular effect of large earthquakes in the marine environment is the generation of seismic sea waves, or tsunamis, which are produced by dislocation of the sea floor. Such waves, when they impinge on coastal areas, can cause extensive battering and flooding and were responsible for much of the damage sustained in the Alaskan earthquake of 1964. Inland, regional displacements may cause surges in lakes, reservoirs, rivers, and canals and permanent changes in water levels that result in flooding, erosion, and drowning of large areas of land. The cumulative effects of land-level changes in the New Madrid, Missouri, earthquakes of 1811 and 1812 destroyed more than 5,000 km^2 of forest, principally by flooding (Coffman and von Hake, 1973, p. 45). In the Hebgen Lake earthquake of 1959, differential subsidence of the lake bottom caused great surges of water that overtopped Hebgen Dam, flooded parts of the shore, and produced large slumps along the banks (Myers and Hamilton, 1964, p. 70-77). The wave surges were particularly damaging to boating facilities along the shore. Warping of the lake bottom caused displacement of the water surface and permanent submergence of a large area along the northeast side of the lake.

Regional horizontal shifts of the Earth's surface, such as those that occurred in the Alaskan earthquake of 1964, produce little if any damage to the land or to manmade structures.

SETTLEMENT

Engineers have long known that masses of sand or gravel, which contain no significant component of clay, can be compacted very effectively by vibration. Thus, the intense shaking produced by earthquakes often leads to compaction of such materials and coincident settlement of the ground surface. In large earthquakes, the amount of settlement resulting solely from vibratory compaction, where liquefaction is not a factor, may amount to a meter or more, even over wide areas such as the floor of an alluvial basin. Quantitative measurements of settlement phenomena largely come from Alaska, where a large effort of scientific study was mounted following the great earthquake there on March 27, 1964 (Eckel, 1970). One of the most accurate measurements of settlement resulting from consolidation and compaction by heavy ground shaking during the Alaskan earthquake was made at Homer Spit, in the southwestern part of the Kenai Peninsula, Alaska, where natural surficial deposits subsided as much as 2½ feet or about 76 cm (Waller and Stanley, 1966, p. D22).

Artificial earth fill is particularly susceptible to compaction by vibratory earthquake motion, and much minor damage during large earthquakes, which in sum can be very disruptive and very costly, is caused by differential settlement of such material relative to adjoining ground or to an adjoining structure or is caused by differential settlement within the material itself. Masses of fill that are especially prone to such movements include railway embankments, road and highway foundations, bridge-abutment backfill, irrigation-canal levees, and supportive pads of gravel or other earth fill beneath buildings and large paved areas such as parking lots and airport runways and aprons. During the magnitude 6.5 San Fernando, California, earthquake of 1971, extensive damage to streets and paved areas was caused by densification and differential settlement of the road foundations (Lew and others, 1971, p. 15). In the magnitude 7.1 Hebgen Lake, Montana, earthquake of 1959, compaction of the roadbeds caused extensive breakage and offset of highway surfaces as well as settlement adjacent to bridge abutments, which lowered highways as much as 2 ft (60 cm) below bridge surfaces (Witkind, 1964a, p. 5-6, fig. 3).

GROUND CRACKING

Ground cracks or fissures commonly form in the epicentral regions of large earthquakes and generally are most abundant in flat terrain underlain by surficial deposits, soft sedimentary rocks, or artificial earth fill. They are largely the result of intense ground shaking and may be considerably enhanced by differential settling. Cracks also form in bedrock along the margins of escarpments or cliffs as a result of shaking, and some fissures are formed in surficial deposits and in bedrock in response to slippage on faults. Primary cracks caused by ground shaking are in many instances difficult to distinguish from those that originate through other mechanisms such as liquefaction-induced movement of the ground surface. Ground cracks in soft earth materials commonly follow streambanks and flood plains, lakeshores, road and railway embankments, and irrigation levees, but in flat country devoid of such features they rarely show a preferred orientation and more generally are arrayed in irregular networks. The cracks mostly range in size from short hairline fractures to fissures 10-20 cm wide and tens of meters long, but cracks of much larger dimension have formed in the source regions of large earthquakes. Generally, the cracks do not extend to depths of more than a few meters. Where formed in loose surficial materials, they are quickly filled with sediment.

During the Helena earthquake of 1935, only a few small cracks opened in the floor of Helena Valley, as mentioned previously. Many ground cracks formed during the earthquake of 1925 near Lombard, Montana. They mainly opened in stream embankments and road foundations within 15-20 mi (24-32 km) of the epicenter (Pardee, 1927, p. 10). In the earthquake at Hebgen Lake, Montana, in 1959, cracking of the ground was widespread along the shores of the lake and in road foundations and road surfaces, and much of the road shattering was due to this cracking and contemporaneous settlement of the road fill (Witkind, 1964a, p. 5-11).

RIDGING AND FURROWING

Two distinct types of ridges and furrows formed in soft ground have been described in association with earthquakes of large magnitude: (1) parallel undulations resembling stationary waves, in which there is a difference in level of as much as a meter between crest and hollow and in which the distance between crests is as much as several meters, and (2) lines of mound-shaped ridges raised along ground cracks. Ridges and furrows of the undulation type were produced on tidal flats in the San Francisco Bay region during the magnitude 8.3 California earthquake of 1906 (Nichols and Buchanan-Banks, 1974, fig. 22) and throughout large areas of the epicentral tract of the magnitude 8.7 Indian (Assam) earthquake of 1897 (Oldham, 1899, p. 95). The undulations that formed in the Indian earthquake were highly disruptive to the agricultural economy of the region, for they were largely formed in ricefields, and extensive releveling of the land was necessary before crops could be grown again. Ridges and furrows associated with ground cracks were formed in a localized area of sandy soil on fairly level ground within the epicentral area of the Indian earthquake of 1897. These ridges were ascribed by Oldham (1899, p. 10-11, fig. 1) to the closing of ground cracks with great pressure, which forced the turf upward along the line of the cracks into distinct ridges. Oldham does not give the dimensions of the ridges, but judging from his illustration they were as much as a meter high.

GROUND CHURNING

Ground churning is a phenomenon associated with earthquakes, wherein parts of the ground and objects on it, such as loose stones, are overturned or thrown into the air with little horizontal displacement. This type of ground dislocation, which has occurred in the epicentral region of several earthquakes of magnitude 6.5 and above, is generally attributed to local ground motion having a vertical acceleration approaching or exceeding that of gravity. Churned ground may form on the surface of solid bedrock, soft surficial deposits, or soils, and in sloping or level terrain; but it is most common in bedrock at the crest of ridges or on other topographic prominences. In the magnitude 6¾ earthquake near Lombard, Montana, in 1925, a thin layer of soil on deposits of clay and sand was intensively shattered and broken into clods that were shifted about and overturned within a zone of ground cracks several feet (1-2 m) wide at the top of a slope above Roy Gulch (Pardee, 1927, p. 10; pl. 12A). Similar overturning of soil on a much larger scale, on fairly level ground, occurred in the magnitude 8.7 Indian (Assam) earthquake of 1897, and, over large areas of bedrock in that earthquake, stones from 25 cm to a meter across were thrown from the ground surface (Oldham, 1899, p. 10-11; p. 130-133). Shattering and overturning of sandstone, limestone, and quartzite occurred on several ridge crests and on other high ground in the vicinity of Hebgen Lake during the magnitude 7.1 Montana earthquake of 1959 (Hadley, 1964, p. 137), and extensive shattering and overturning of soil occurred on an isolated ridge crest in the magnitude 6.5 San Fernando, California, earthquake of 1971 (Nason, 1971, p. 97-98). Apparently, no damage to manmade structures has resulted from earthquake ground churning, but considerable disruption of wide tracts of land was caused by the overthrow of sod in the Indian earthquake of 1897.

SEICHES AND SURGES

Seiches (pronounced sāshes) are oscillations of the surface of lakes, ponds, rivers, reservoirs, and bays that travel back and forth across the water surface at regular periods determined by the depth and size of the water body. The oscillations are in the form of standing waves and may be likened to the sloshing of water in a container when it is suddenly jarred. Seiches usually originate from wind stress, unusual tides or currents, or sudden changes in atmospheric pressure, but in some instances they are produced by earthquake ground motion. Earthquake shaking moves the water back and forth and sets up waves that can cause flooding of shoreline facilities and erosion of the land. In general, seiche waves generated by earthquakes are of low amplitude and no more than a few tens of centimeters high, but waves as much as several meters high may result where water is constricted, as in the narrow arm of a lake, or where a body of water shallows abruptly near the shoreline. Waves as high as 20 ft (6 m) were produced in a constricted part of Kenai Lake, Alaska, during the earthquake of 1964 (McCulloch, 1966, p. A30). Damaging seiches may also occur in industrial or municipal storage tanks during earthquakes, and quasi-resonance between the ground vibrations and the oscillations of water can produce damaging water motion even at large distances from an earthquake source. During the Nevada earthquake of December 16, 1954, weak ground shaking related to long-period motion produced damaging oscillations in the city reservoir and in industrial tanks in Sacramento, California, some 240 km from the epicenter (Steinbrugge and Moran, 1957, p. 338-348).

Sudden regional warping or tilting of the land beneath bodies of water during earthquakes also may cause intense seiching of the water surface, as was mentioned earlier in the section on "Regional land displacement." The initial wave generated by warping may be as much as several meters high, and subsequent oscillations, which may continue for several hours after the initial disturbance, are of gradually diminishing intensity and amplitude. In the Hebgen Lake, Montana, earthquake of 1959, the water oscillations caused by subsidence of the lake bottom continued for at least 12 hours after the earthquake (Myers and Hamilton, 1964, p. 70). The large oscillations of water produced by land warping are generally called surges to distinguish them from ground-shaking-induced seiches, which ordinarily are of much smaller amplitude and destructive force.

LOCAL GEOLOGIC CONDITIONS THAT MAY CONTRIBUTE TO SEISMIC HAZARDS

Because seismic hazards involve movements of the ground surface, their level of severity is influenced to a large degree by the geologic setting at an earthquake site. The potential location and size of destructive earthquakes, the potential level of damaging ground shaking, the potential for ground failure, and the potential for flooding are all closely determined by the nature and distribution of geologic rock units and faults, the topography, and the size and extent of water bodies in the affected region. Moreover, owing to local differences in geology, the amplitude of ground motion and the extent of ground failure in any earthquake may vary widely from place to place, even at the same distance from the earthquake source.

Like most seismically active regions of the world, the Helena area is host to a variety of geologic conditions that may contribute to seismic hazard. These conditions include: (1) the widespread occurrence of surficial deposits prone to amplified shaking and ground failure, (2) the abundance of steep bedrock slopes prone to landsliding, (3) the occurrence of geologic faults susceptible to surface rupture, and (4) the presence of hydrologic features that create a potential for flooding. Geologic and seismologic data in the Helena area are not yet sufficient, however, to evaluate these conditions in other than a very general way; therefore, precise estimates or predictions of their potential effect in future earthquakes cannot be made. Nevertheless, the elementary assessment presented herein should be useful in identifying problem areas and establishing broad land-use guides aimed at minimizing earthquake hazards.

SURFICIAL DEPOSITS

Surficial deposits underlie more than a third of the area, including most of the floor of Helena Valley, a broad tract of land at the south end of Silver Valley, and much of the low land along major streams (pls. 1, 2). In Helena Valley, large parts of Helena and Fort Harrison, the whole of East Helena, and much land undergoing rapid urban development in Lewis and Clark County are underlain by unconsolidated and weakly consolidated surficial units. The significance of the surficial deposits, insofar as earthquakes are concerned, is twofold: (1) ground motion tends to be amplified in these rocks, and (2) the deposits are susceptible to ground failure from landsliding, liquefaction effects, settlement, and cracking. It follows that the most widespread damage in a future destructive earthquake is likely to occur in areas underlain by these materials.

A general appraisal of the response of the surficial deposits to ground shaking during the Helena earthquake of 1935, the expected response of the surficial deposits to ground shaking in future earthquakes, and the susceptibility of the surficial deposits to various types of ground failure is given following.

RESPONSE TO GROUND SHAKING IN THE 1935 EARTHQUAKE

Structural damage in and near Helena during the earthquake of 1935 was largely confined to buildings constructed on surficial deposits; in most instances, it was very light or nonexistent in structures built on or anchored to bedrock. In general, the buildings that sustained severe damage on surficial deposits were comparable in size and type of construction to buildings that escaped damage on bedrock. The areas of worst damage, in which numerous buildings sustained fallen walls and roofs and other serious structural deformation, were along the northern margin of the city and in its northeastern, central, and south-central sections where structures were built on stream deposits, slope wash, and older gravel.

The general correlation between extensive damage and surficial deposits is illustrated on plate 3, which shows the distribution of surficial deposits and bedrock, the traces of geologic faults, and the location of buildings heavily damaged in the earthquake of 1935. The correlation suggests that seismic shaking was intensified on the surficial materials.

In the south-central part of the city, heavy building damage may have been related to amplified motion in accumulations of young surficial deposits that form a thin cover on bedrock over much of that area. The extensive damage in the upper part of Last Chance Gulch, for example, was attributed to amplified shaking in stream deposits that had been loosened and redistributed by early placer operations (Neumann, 1937, p. 47-48). East of the gulch, between Warren and Davis Streets, damage probably was caused mainly by intensified shaking of the older gravels that cap the low, flat-topped bedrock ridge running northward through that part of the city. Farther east, amplified motion in slope wash near bedrock outcrop may account for the widespread damage to residential structures along Breckenridge, Hillsdale, and Highland Streets.

The greatest incidence of damage to larger buildings from the 1935 earthquake occurred in the central and eastern parts of Helena and along its northern margin, which are underlain at shallow depth by older stream and lake deposits of Tertiary age (pls. 1, 3). These deposits, which consist largely of soft clay, overlap sedimentary and plutonic bedrock and underlie a thin veneer of younger surficial deposits. In Helena, the contact between the older strata and the bedrock, which is mostly concealed, winds through the city from St. Peter's Community Hospital on the east to the Kessler Brewery on the west and passes just north of the Capitol building and Carroll College. The contact represents the edge of the interface between the older stream and lake deposits and the bedrock, and presumably this interface dips gently northward and lies at moderate depth (0-200 m) beneath the city. The general restriction of major building damage to the area underlain by the older stream and lake sediments may signify that ground shaking was significantly amplified in the wedge of older strata at the south margin of Helena Valley and was perhaps further heightened in the overlying thin layer of younger surficial materials. However, because so many other factors were involved in producing structural damage, the influence of the older stream and lake deposits on ground shaking is problematical.

A unique structural failure at the Kessler Brewery that was observed by A.F. Bateman, Jr. and the late C.E. Erdmann of the U.S. Geological Survey a few weeks after the 1935 earthquake may indicate that ground shaking was amplified at that locality. As described by Bateman (oral commun., 1977), round steel rest plates beneath vertical steel-plate supports at the ends of filled stainless-steel brewing tanks were driven downward as much as 7.5 cm into the concrete floor (ground floor) of the brewery by the force of the earthquake ground motion. The steel rest plates were about 2.5 cm thick and 30 cm in diameter, and the steel-plate supports were about 12 cm wide, 2.5 cm thick, and 40 cm long. The brewing tanks were cylindrical, about 2.5 m in diameter and 4 m long, and the concrete floor was about 85 cm thick. The margins of the depressions formed beneath the rest plates were clean and sharp, which suggests that the plates were punched into the concrete surface. This phenomenon occurred only beneath filled tanks; the floor beneath empty tanks was not so affected. The brewery, which is on the far west side of Helena (pl. 3), stands on about 10 m of flood-plain gravel along Tenmile Creek. The gravel, in turn, rests on older stream and lake deposits, which are at least 100 m thick as indicated in water wells to the north and east. The force that drove the rest plates into the brewery floor may have resulted either from sudden, strong upward movements of the brewery floor and the inertial resistance of the tanks to such movement or from intense rocking of the tanks in response to intensified ground shaking at the brewery site. The stream gravel beneath the structure is normally saturated with water below a depth of about 2 m; the older stream and lake deposits that underlie the gravel also are water saturated. This condition may have contributed greatly to enhance shaking in the vicinity of the brewery, for observations show, generally, that earthquake ground motion is strongly amplified and has increased duration on water-saturated sediments.

EXPECTED RESPONSE TO GROUND SHAKING IN FUTURE EARTHQUAKES

Field studies at earthquake sites have shown that the intensity of ground shaking can vary greatly in different types of surficial deposits, and, in recent years, considerable work has been focused on the development of quantitative techniques to predict the vibratory response of these materials under conditions of earthquake loading. The investigations of Gutenberg (1957); Borcherdt (1970); and Borcherdt, Joyner, and others (1975) concerning ground-motion amplification in surficial deposits have been mentioned in the preceding section on "Ground shaking." Other studies dealing with the dynamic response of surficial materials to earthquake ground motion, aimed mainly at establishing design criteria for engineering structures, have been made by Seed and Idriss (1969, 1971), Seed and Schnabel (1972), and Seed and others (1974), and a general treatment of the problem as it relates to earthquake-resistant design has been presented by Dowrick (1977, p. 44-79). Probably the most elaborate investigation of the subject is that of the seismologist Medvedev (1965, p. 38-55), who has quantified the effects of different rock types and other geologic factors on earthquake intensity for the purpose of seismic microzonation (the delineation of geographical areas with different earthquake-hazard potential) in the U.S.S.R.

Physical characteristics of surficial deposits, such as bulk density, seismic body-wave velocities, thickness, and degree of water saturation, as well as the effects on the deposits of small natural earthquakes and distant nuclear testing, have been used to analyze the shaking behavior of these materials. Because these factors are largely unknown for the surficial units in the Helena area, however, only a very simplified assessment of the expected response of the materials in future earthquakes, based mainly upon data from other areas, can be given here. The work of Medvedev (1965, p. 45-52) on the relation of seismic intensity to the character of the ground is particularly relevant in this regard, and a brief outline of his findings is provided here.

MEDVEDEV'S DATA

To introduce the factor of rock type in seismic microzonation, Medvedev (1965, p. 45-46) made use of relations termed the seismic-intensity increment and the seismic impedance of various basic categories of ground that he designated as (1) granites, (2) limestones and sandstones, (3) moderately firm ground, (4) coarse-fragmental ground, (5) sandy ground, (6) clayey ground, and (7) loose fill. The seismic-intensity increment, which is the increase in shaking intensity on a particular type of ground relative to the shaking intensity on granite, is based on the GOST intensity scale[2] used in the U.S.S.R. The intensity increments of the various types of ground were determined from field studies of earthquake intensities at numerous localities in the Soviet Union where the effect of factors other than rock type was minimal. The seismic impedance of the ground is defined as the product of the velocity of the primary or longitudinal seismic waves (*P* waves) in the various classes of ground and the bulk density of the materials, or $V_p\rho$, the component parameters having been ascertained from seismic prospecting data and from on-site density measurements. Table 2 shows the seismic-intensity increment *P*-wave velocity, bulk density, and seismic impedance of the basic types of ground as determined by Medvedev (1965, tables 2.1 and 2.2, p. 46-47), and from this data he derives (Medvedev, 1965, p. 46) a mathematical relation between the seismic-intensity increment and the seismic impedance in the form

$$n = 1.67 \quad [\log(V_p\rho \text{ granite}) - \log(V_p\rho \text{ ground})],$$

where n is the seismic-intensity increment and 1.67 is an empirically determined correlation factor.

The seismic-intensity increments listed in table 2 apply to ground in a natural state of moisture, but Medvedev (1965, p. 49) recognized from studies of earthquake effects that shaking intensity in unconsolidated deposits is markedly influenced by the water-table level in the ground. On the basis of observations of seismic intensity on sandy loams, loams, and fine sands and on the basis of other data, he concluded (Medvedev, 1965, p. 49) that (1) where the water-table depth is below 10 m the seismic intensity is not affected, (2) where the water-table depth is roughly 4 m the seismic intensity increases by about half a unit, and (3) where the water-table depth is 1 m or less the intensity is increased by one unit. From these relations Medvedev (1965, p. 49) obtained an equation expressing the increase in seismic intensity of a given area of ground as a function of water-table elevation such that

$$n_b = e^{-0.04h^2},$$

where n_b is the increase in seismic intensity, e is the base of the natural logarithm, and h is the depth to the water table in meters below the ground surface. Taking water-table depth into account, he obtained a final formula (Medvedev, 1965, p. 49) for the seismic-intensity increment in the form

$$n = 1.67 [\log(V_p\rho \text{ granite}) - \log(V_p\rho \text{ ground})] + e^{-0.04h^2}.$$

This equation has been used to compute seismic-intensity increments for common types of ground at earthquake sites in the U.S.S.R., where such factors are widely applied as a general standard for seismic microzonation and for adapting the design of engineering structures to natural foundation conditions. The standard seismic-intensity increments calculated for different types of ground are listed in Medvedev's report (1965, table 2.5, p. 50).

[2]The GOST intensity scale, which has 12 intensity ratings, is broadly similar to the Modified Mercalli Intensity Scale presented in the appendix to this report.

TABLE 2.—*Seismic characteristics of basic types of ground as determined by Medvedev (1965)*

Ground	Seismic-intensity increment	V_p (km/s)	ρ Bulk density (g/cm³)	$V_p\rho$ Seismic impedance
Granites	0	5.6	2.9	16.2
Limestones and sandstones	0–1	4.5–2.5	2.8–2.0	12.6–5.0
Moderately firm ground (gypsum, marl)	1	3.0–1.7	2.4–1.7	7.2–2.9
Coarse-fragmental ground (rubble, pebble, gravel)	1–2	2.1–0.9	2.0–1.6	4.2–1.4
Sandy ground	1–2	1.6–0.6	1.9–1.6	3.1–1.0
Clayey ground	1–2	1.5–0.6	2.0–1.6	3.0–1.0
Loose fill	2–3	0.6–0.2	1.5–1.3	0.9–0.26

In general, Medvedev's data indicate that the intensity of seismic shaking on unconsolidated surficial deposits (coarse-fragmental, sandy, and clayey grounds) is markedly greater than the intensity of seismic shaking on firm rock or bedrock (granite, compact sedimentary rock) and is greatest on loose fill. Specifically, his results predict that shaking intensity, as measured by the GOST intensity scale, may increase on coarse-fragmental ground by as much as 1.5 units, on sandy and clayey grounds by as much as 2 units, and on filled land by as much as 3 units over the intensity on adjacent granite, and that these intensities may further increase by a whole unit if the unconsolidated grounds are saturated with water. His studies also show that ground-motion intensity on compact sedimentary rocks (limestones, shales, sandstones) is somewhat greater than the intensity on granite and that shaking intensity on moderately firm ground such as marl may be as much as a whole unit higher than the intensity on granite. Moreover, his data demonstrate (table 2) that the intensity of seismic shaking on different types of ground generally increases as the seismic impedance of the rocks decreases and that seismic impedance broadly correlates with the overall firmness or hardness of the ground. The potential contrast in the shaking intensity of various rock units therefore can be determined in a rough way on the basis of field observations.

CORRELATION WITH MEDVEDEV'S BASIC CLASSES OF GROUND

Some of the rock units in the Helena area have close counterparts among the basic classes of ground subjected to seismic analysis by Medvedev (1965). In particular, the plutonic and volcanic bedrock in the area probably corresponds rather closely to his granites; the sedimentary bedrock to his compact limestones and sandstones; the older gravel to his coarse-fragmental ground; the wind-laid and glacial-lake deposits to certain of his sandy and clayey grounds; and the artificial fill, and placer tailings, and landslide deposits to his loose fill. The correlation of the stream deposits, slope wash, and older stream and lake deposits in the Helena area with Medvedev's ground types is less certain.

The stream deposits unit consists mainly of gravel and, for the most part, probably can be equated with Medvedev's coarse-fragmental ground. Locally, however, this unit includes substantial amounts of sand and clay and, figuratively, is more or less a mixture of his coarse-fragmental, sandy, and clayey grounds. The slope wash unit is largely gravel with a matrix of sandy to silty clay, and the proportion of matrix in the gravel is usually greater than that of the rock fragments. The gravelly slope wash therefore corresponds to a mixture of Medvedev's coarse-fragmental and clayey grounds. The older stream and lake deposits unit consists largely of firm clay, weakly cemented sand and gravel, and compact volcanic ash, and the bulk of the unit therefore may broadly correspond to Medvedev's moderately firm ground in terms of seismic characteristics. In some areas, however, the rocks are less firm and include much soft bentonitic clay and clay-altered volcanic ash that probably correspond closely to Medvedev's clayey ground. The clayey rocks form a large part of the unit in the eastern and northern sections of the city of Helena and in the northwestern part of the Helena quadrangle.

The general correlation of the Helena rocks with Medvedev's basic categories of ground is shown in table 3.

GENERAL RESPONSE OF SURFICIAL UNITS

To a large extent, the amplification of ground motion in surficial deposits depends on the fundamental vibrational frequency of the materials, which is largely controlled by the thickness of and the seismic shear-wave (*S*-wave) velocity in the materials. Therefore, Medvedev's (1965) intensity increments for various classes of unconsolidated ground, which are based on seismic impedance values calculated from *P*-wave velocities and which do not take thickness into account, are not wholly accurate or reliable. It follows that estimates of intensity increments for surficial materials based on approximate comparisons with Medvedev's basic types of ground are even less reliable. Nevertheless, pending the acquisition of better data, the estimates based on such comparison and presented here for surficial units in the Helena area

TABLE 3.—*Correlation of rock units in the Helena area with Medvedev's (1965) basic categories of ground*

Medvedev's basic categories of ground	Helena rock units, this report	
Firm ground: Granites Limestones and sandstones	Plutonic and volcanic bedrock Sedimentary bedrock	
Moderately firm ground	Older stream and lake deposits (bulk of unit)	
Coarse-fragmental ground	Older gravel	Stream deposits Slope wash
Sandy ground	Wind-laid deposits Glacial-lake deposits	Stream deposits Slope wash
Clayey ground	Bentonitic clays of the older stream and lake deposits unit	Stream deposits Slope wash
Loose fill	Artificial fill, placer tailings, landslide deposits	

serve as a rough guide to the potential seismic response of the deposits in future earthquakes.

On the basis of the correlation with Medvedev's basic grounds, the rock units at Helena can be grouped into five categories according to similarities in potential seismic response as shown in table 4. The seismic-intensity increments assigned to each grouping roughly indicate the expected increase in potential shaking intensity from one category to another. These increments are based on the GOST intensity-scale values determined by Medvedev (1965, tables 2.3 and 2.5, p. 48, 50) for similar types of rock in the Soviet Union but are broadly interpreted to conform to the Modified Mercalli Intensity Scale of 1931, given in the appendix to this report.

A rough estimate of the expected response of the rocks in future earthquakes can be made from the groupings in table 4. Generally, the data show that the intensity of ground shaking on the surficial rocks is expected to be substantially greater than the intensity of shaking on bedrock and that significant variations in shaking intensity can be expected among different categories of surficial materials. More specifically, the groupings imply that ground-motion intensity will be weakest on plutonic and volcanic bedrock, slightly greater on sedimentary bedrock, intermediate on the bulk of the older stream and lake deposits, stronger on the uncemented surficial units, and greatest on loosely compacted artificial fill, placer tailings, and landslide deposits. In terms of Mercalli-scale units, the intensity of shaking relative to that on plutonic and volcanic bedrock is expected to increase by as much as 0.5 unit on sedimentary bedrock; by as much as 1 unit on the bulk of the older stream and lake deposits; by as much as 2 units on stream deposits, slope wash, wind-laid deposits, glacial-lake deposits, older gravel, and older bentonitic clays; and by as much as 3 units on artificial fill, placer tailings, and landslide deposits. These increases are in general accord with ground-motion effects that took place in the Helena earthquake of 1935, during which shaking on surficial materials was locally of intensity VIII but on bedrock was of intensity VI or less.

As pointed out by Medvedev (1965, p. 49), the intensity of earthquake ground shaking is enhanced in surficial deposits where the water-table level is close to the ground surface and may increase by as much as a whole GOST-intensity unit where the depth to water table is 1 m or less. Gutenberg (1957, p. 235) also noted a remarkable increase in shaking intensity on water-saturated ground. In the eastern part of Helena Valley, where the surface is covered by young stream deposits, the water table is generally within 12 ft (3.6 m) of the ground surface, and, over much of this area, it is at a depth of 6 ft (1.8 m) or less, especially during the period of summer irrigation. The general limit of the tract with shallow water table is shown by lines of equal water-table depth on plates 1 and 2. These lines apply to the month of September, but, because the water table fluctuates seasonally, a much larger area of valley ground may be saturated at shallow depth during the spring months when precipitation is greatest. Other bodies of surficial rock that are permanently saturated with water at shallow depth are present along perennial streams, lakes, and reservoirs in the region. Ground shaking in the areas of shallow water table can be expected to be intensified in future earthquakes of destructive magnitude.

SUSCEPTIBILITY TO GROUND FAILURE

DEPOSITS PRONE TO LANDSLIDING

Earthquake-triggered landslides are especially common in surficial deposits and soils on steep slopes, but slides also may occur in these materials on low slopes,

TABLE 4.—*Rock units of the Helena area grouped according to relative seismic response*

Category	Seismic-intensity increment (range)	Rock units
1	0	Plutonic and volcanic bedrock.
2	0–0.5	Sedimentary bedrock.
3	1	Older stream and lake deposits (bulk of unit).
4	1–2	Older gravel, stream deposits, slope wash, wind-laid deposits, glacial-lake deposits, and bentonitic clays of the older stream and lake deposits unit.
5	2–3	Artificial fill, placer tailings, and landslide deposits.

even in terrain that is virtually flat, as a result of liquefaction of water-saturated ground. Surficial materials in the Helena area that are particularly susceptible to landsliding are present on steep hill and valley slopes, in streambank and lakeshore scarps, at terrace margins, and in artificial embankments and excavations. Old landslide deposits also may be subject to renewed movements during earthquakes. The most prominent of these landslide-prone sites are broadly identified in this section of the report.

Slope wash along the mountain front at the southern margin of Helena Valley locally mantles slopes that range from 15 to 40 percent. These materials may be highly susceptive to slumps and earthflows in a large earthquake, especially if their moisture content is high, as might result during periods of prolonged rainfall. The main masses of steeply inclined slope wash are at the north end of the Elkhorn Mountains (pl. 2), along the mountain front east of Helena near the Lewis and Clark County-Jefferson County boundary (pl. 2), on the upper west side of Helena (pl. 1), on hillsides south and west of Fort Harrison (pl. 1), and along the east flank of the Scratchgravel Hills (pl. 1). Many smaller masses of slope wash on steep mountain slopes (not delineated on pls. 1 and 2) also may have a strong tendency to fail by landsliding in future earthquakes.

Steep valley sides and steep slopes at the front of benches and terraces formed in surficial deposits are potential sites of slumping, debris sliding, and rockfall in future strong earthquakes. In the eastern part of the area (pl. 2), slopes as steep as 60 percent and more are present in surficial materials along Spokane Creek and its tributaries and along valleys and scarps cut into Spokane Bench, cut into the rolling terrain north of the Elkhorn Mountains, and cut into the broad benchland southwest of East Helena. The slopes along Spokane Creek and its larger tributaries are as much as 40 m high and along the other valleys as much as 25 m high. Other steep slopes, which are mostly less than 6 m high and in places almost vertical, are formed in surficial deposits along ravines in Helena Valley north and northwest of Lake Helena, on the northern flank of the Spokane Hills, and in the eastern outskirts of Helena. In the western part of the area (pl. 1), scarps with slopes of more than 60 percent and heights of as much as 4 m are locally present in surficial materials along the narrow ravine east of Sanders Street, along the east side of Dry Gulch north of Harlow Street, and along the east side of Last Chance Gulch west of Willard Avenue in the city of Helena; along ravines in the vicinity of Fort Harrison; and along ravines in the northwestern part of Helena Valley. Slopes of 60 percent and more and as much as 10 m high are locally formed in surficial deposits at the margins of the valleys of Silver and Threemile Creeks and tributary streams in the northwestern part of the area.

Streambank and lakeshore scarps are prone to slump failure in large earthquakes and are frequently the site of earth lurching in shocks of high magnitude and long duration (see fig. 11*D*). Steep streambank scarps are locally formed in stream deposits along Spokane, Prickly Pear, Tenmile, Sevenmile, and Silver Creeks and, to a lesser extent, along smaller tributary streams. These scarps are generally 1-2 m high, but locally are as much as 5 m high. Commonly they are vertical. Much of the shoreline of Lake Helena is marked by a vertical or near-vertical scarp 1-2 m high formed in surficial deposits; steeply inclined to vertical scarps as much as 10 m high are locally present in glacial-lake sediments and other surficial units along the shores of Hauser Lake on the Missouri River, chiefly at Eldorado Bar, at the west side of the lake (river) south of the York bridge, at Metropolitan Bar, and near Lakeside (pl. 2).

Gravel in the steep free face of river and stream terraces might be dislocated by rockfall and debris sliding during strong earthquakes. In the eastern part of the area (pl. 2), slopes of this sort are common in older gravel along the Missouri River at Eldorado Bar, Danas Bar, McCune Bar, Spokane Bar, and Gruel Bar and to a lesser extent along McClellan Creek, Holmes Gulch, and Prickly Pear Creek. In the western part of the area (pl. 1), steep slopes are locally present at the margins of gravel-covered terraces along Sevenmile Creek and Skelly Gulch west of Birdseye, along the lower part of Park Creek north of Birdseye, and along Silver and Threemile Creeks.

Steep embankments of artificial fill may be dislocated by slumping, settlement, and cracking during severe earthquakes and may be subjected to massive failure by earth lurching in shocks of high magnitude and long duration (fig. 11*D*). In the Helena area, embankments of earth and rock fill are present along roads and railways, along irrigation and drainage canals, at earth dams, and at the Lake Helena causeway. The piles of smelter slag at East Helena, which are as much as 15 m high, also can be regarded as large embankments. The highest road embankments, which are elevated as much as 6 m above ground level, are along Interstate Highway 15 at a ravine-crossing about 1 km north of the area boundary, in ramps built at Lincoln Road and Sierra Road on the floor of Helena Valley, and in ramps built at Custer Avenue, Cedar Street, and Prospect Avenue (U.S. Highway 12) in the eastern outskirts of Helena. Railway embankments are generally low, but in places are as much as 3 m high. The earth embankments along irrigation and drainage canals are mostly 1-2 m high, but are as much as 6 m high at several places along the main irrigation canal where it crosses ravines in the eastern part of the area. The largest earth dams are at the Helena Valley Regulating Reservoir in the eastern part of the area (pl. 2) and at the Gehring and Hardie Reservoirs on Threemile Creek in the western part of the area (pl. 1).

The failure of embankments during earthquakes commonly results in losses of impressive proportions, and care must be taken in the design of these features in seismically active regions to guard against earthquake damage. A broad summary of the types of earthquake-induced failure common to earth embankments and earth dams and a review of engineering methods used to analyze and improve the stability of such structures have been presented by Okamoto (1973, p. 255-277; 427-490). Sherard (1967) has reviewed earthquake considerations that pertain to the design of earth dams; Chopra (1967) has investigated the response of earth dams to earthquake ground motion; and Seed and Martin (1966) have examined the use of seismic coefficients in earth dam design.

Surficial materials in the walls of road and railway cuts, irrigation and drainage canals, and gravel pits commonly undergo slumping and rockfall during intense earthquakes. Most road cuts in the Helena area that are excavated in surficial units are shallow and between 1 and 2 m deep; a few cuts made in older stream and lake deposits along York Road and along U.S. Highway 12 in the eastern part of the area are as much as 5 m deep. The largest railway cuts, as much as 6 m deep, are in gravelly deposits along the Burlington-Northern tracks east of East Helena. The main irrigation and drainage canals in Helena Valley are as much as 3 m deep. Numerous steep-sided gravel pits, some with vertical walls as much as 6 m high, are excavated in stream deposits and slope wash in Helena Valley. The location of the principal pits is shown on plates 1 and 2.

Reactivation and slumping of the margins, particularly the toe portions, of old landslide masses at the head of Park Gulch (pl. 1) and on the northern slope of the Elkhorn Mountains (pl. 2) might occur in a strong earthquake.

DEPOSITS PRONE TO LIQUEFACTION

Seismically induced liquefaction, which is responsible for some of the most striking and most damaging types of failure in surficial materials (see section on "Liquefaction-induced failure"), ordinarily occurs in layers and lenses of loose, well-sorted, water-saturated sand and silt within 30 m of the ground surface. In the Helena area, permanently saturated sand and silt in stream deposits on the floor of Helena Valley and on flood plains, in glacial-lake deposits and other surficial units along the shores of Lake Helena and Hauser Lake, and in some embankments of artificial fill have the highest potential for liquefaction. Sands and silt in the slope-wash unit, and wind-laid sand and silt, are rarely saturated with water and generally are not liquefiable during most of the year, but certain of these deposits may be highly susceptible to liquefaction if they are water saturated. Sand and silt in older gravel and in the older stream and lake deposits unit are unlikely to undergo significant liquefaction. A further assessment of the liquefaction potential of the surficial deposits and of the effects that liquefaction may induce in them during strong earthquakes is presented in the following discussion.

Stream deposits on the floor of Helena Valley probably contain a large volume of potentially liquefiable sand and silt, for over much of this area the ground-water table is at a depth of 12 ft (3.6 m) or less (pls. 1, 2). A minor amount of liquefaction occurred on the valley floor near Lake Stanchfield and at a few other localities during the Helena earthquake of 1935, as evidenced by the issuance of water and sand from cracks in the ground (fig. 9), and very likely the process would increase markedly in an earthquake of larger magnitude. Conceivably, liquefaction could lead to damaging quick-condition effects on the valley floor, such as differential settlement of the ground, or even to a condition of general upward seepage and ejection of water at the land surface that might cause structures to settle into the soil. In some great earthquakes (magnitude >8.0), liquefaction of basin fill has produced intense fountaining of water and sand from fissures and vents that has flooded the land and has filled stream channels, drainage ditches, and other low areas with sediment. However, the possibility of such an extreme effect occurring on the floor of Helena Valley is remote. Beds of water-saturated sand and silt also may be present in the deeper portion of floodplain deposits along major streams. Liquefaction of these sediments in a strong earthquake might lead to quick-condition effects along those drainages.

Glacial-lake deposits, stream deposits, and slope wash along the shores and beneath the waters of Lake Helena and Hauser Lake contain sand and silt that are potentially liquefiable. The glacial-lake deposits may be especially susceptible to liquefaction, for they are largely composed of beds of clean, well-sorted sand and silt. Liquefaction of the near-shore and underwater sediments could cause lateral-spreading or flow landslides or both that would involve sizable tracts of shoreline land. Movement of flow landslides into the lakes or movement of underwater flow slides might produce strong wave surges.

Fine-grained, water-saturated artificial fill also is prone to liquefaction, and, in many instances, slumping and settlement of earth embankments and other masses of loose fill during earthquakes have been ascribed to liquefaction. In the Helena area, irrigation-canal embankments and earth dams built largely of surficial materials may contain potentially liquefiable sand and silt. Road embankments and other bodies of earth fill that stand above the ground surface are ordinarily well drained and are not susceptible to liquefaction unless they become saturated with water during heavy or prolonged rainfall or from snow melt. Railway embankments, which are mostly built of solid rock fragments, are generally not liquefiable.

Sand and silt in the slope-wash unit have a low liquefaction potential, for this material mainly lies on well-drained sloping surfaces and is unsaturated with water during much of the year owing to the prevailing dry climate. During the wet spring months and during periods of abnormally high rainfall, however, some slope wash is likely to become saturated, especially the distal parts of broad aprons of the sediment in the western part of Helena Valley—for example, the large accumulations that underlie the eastern and western sections of Helena (pls. 1, 2). Seismically induced liquefaction of saturated sand or silt in the slope wash conceivably could lead to the formation of lateral-spreading landslides over wide areas of ground on the gently inclined portions of these deposits. Masses of slope wash on steep to moderate slopes may occasionally become saturated from heavy rainfall or snow melt. Liquefaction of sand or silt in these materials might produce flow landslides.

Wind-laid deposits on the flanks of the Spokane Hills and at localities along the Missouri River (pl. 2), much of which consist of the type of silt called loess, lie on high ground above the water table and ordinarily are not liquefiable. If these sediments became saturated with water from excessive rainfall or snow melt, however, they might be capable of extensive liquefaction and flow sliding in a strong earthquake. The potential for such behavior in loess is suggested by the widespread failure of the material in historic earthquakes, notably those that occurred in Kansu Province, China, in 1920 (Willis, 1922) and along the Mississippi River near New Madrid, Missouri, in 1811 and 1812 (Fuller, 1912, p. 59-61).

Sand and silt in older gravel and in older stream and lake deposits are unlikely to become liquefied in future earthquakes. The older gravel, which lies above the water table, is rarely saturated; and sand and silt are not abundant in the unit. Furthermore, the older gravel is generally dense and well compacted and probably would resist dislocation even if liquefaction were to occur. Sand and silt in the older stream and lake deposits unit are mostly dense and partly cemented and generally may be incapable of significant earthquake-induced liquefaction. The water-table level in these deposits, apart from material at lakes and reservoirs and near flowing streams, is mainly at depths greater than 10 m, which further lessens the possibility of liquefaction. Moreover, the compact and coherent state of the older stream and lake sediments probably would prevent much liquefaction-induced movement in them.

DEPOSITS PRONE TO SETTLEMENT

Intense vibration of the ground during strong earthquakes commonly leads to compaction of loose surficial materials and to settlement of the ground surface. This kind of dislocation, which can occur either in dry or in saturated sediments and which can effect ground subsidences of as much as a meter or more, may produce damage to engineering structures supported on, or built of, the compacted materials. Substantial settlement of the land surface also can result from densification or from lateral spreading of liquefied sediments beneath the ground surface. Often, the precise cause of ground settlement cannot be determined.

Surficial materials in the Helena area that may be particularly susceptible to seismically induced compaction and settlement include artificial fill, placer tailings, landslide deposits, and stream deposits. Slope wash, wind-laid deposits, and glacial-lake deposits are probably capable of densification to a lesser degree; older gravel and older stream and lake deposits are comparatively dense and firm and are unlikely to undergo significant compactive settlement from earthquake ground shaking.

DEPOSITS PRONE TO CRACKING

Horizontal oscillation of the ground during strong earthquakes commonly produces surface cracks that range from short hairline fractures to deep fissures many centimeters wide and hundreds of meters long in loosely consolidated surficial deposits. This cracking, which may be accompanied by differential settlement of the ground surface, can cause serious damage to structures built of surficial materials and to structures buried in the deposits. Although only a few ground cracks were formed in surficial materials during the Helena earthquake of 1935 (magnitude 6¼), a much greater incidence of cracking can be expected to take place in a future shock of larger magnitude.

Surficial deposits in the Helena area that are most susceptible to earthquake-induced ground cracking are masses of artificial earth fill such as road and railway foundations, irrigation- and drainage-canal embankments, and earth dams. Placer tailings also may be highly susceptible to this kind of dislocation. Other materials prone to cracking include stream deposits, slope wash, glacial-lake deposits, and wind-laid deposits of loess, particularly along streambanks and lakeshores. The older gravel and the older stream and lake deposits, which are generally firmer than the other surficial materials, probably would undergo significant cracking only in major or great earthquakes (magnitude >7.0).

STEEP BEDROCK SLOPES

Because landsliding takes place more readily and with greater frequency on steep slopes, it is most likely to occur in the mountainous parts of the Helena area in future earthquakes of destructive magnitude. Now, however, it is not possible to predict precisely where, or at what specific level of earthquake ground shaking, landsliding on the mountain slopes will occur, for quantitative data are not available on the stability of slopes in this region.

Steep slopes on bedrock that are potential sites of earthquake-induced landsliding are especially common in the Scratchgravel Hills, in the mountains south and west of Helena, along the northern slope of the Elkhorn Mountains, on the west flank of the Spokane Hills, in escarpments along the Missouri River, and in the Big Belt Mountains (pls. 1, 2). The precipitous slopes on the flanks of Mount Ascension and Mount Helena, slopes at the eastern front of the Scratchgravel Hills, and slopes along the upper parts of Last Chance Gulch and Dry Gulch and the valley of Tenmile Creek pose a threat to urbanized areas. The north-facing limestone cliff near the summit of Mount Helena, which rises steeply above the western section of the city of Helena, may be particularly hazardous in terms of its potential susceptibility to earthquake-triggered landsliding. Although this precipice showed no evidence of dislocation during the earthquake of 1935, it might be prone to rockfall or perhaps even to massive landsliding during a stronger earthquake, for example in the range of magnitude 6.5-7.0.

Although steep slopes are common in the area, only two large landslides have been recognized: one at the head of Park Gulch in the northwestern part of the Helena quadrangle (pl. 1) and the other along the steep northern slope of the Elkhorn Mountains in the southeastern part of the East Helena quadrangle (pl. 2). Tree growth indicates that these slides originated scores of years ago. The Park Gulch slide, which consists of a tonguelike mass of angular blocks of quartzite shed from the mountain mass that rises above it on the west, is doubtfully related to seismic shaking. The slide at the northern front of the Elkhorn Mountains is a large slump detached from a steep mass of volcanic bedrock. It might have been activated by earthquake vibrations, but other causes for its origin are equally plausible.

FAULTS

The earthquake hazard associated with faults is threefold: (1) earthquakes may originate on them, (2) surface rupture and strong ground shaking may occur along or near them, and (3) regional ground displacement may be associated with them. Geologic evidence indicates that earthquakes generally occur on active faults and are rarely associated with inactive fractures (Bonilla, 1970, p. 68). The recognition of active or potentially active faults is therefore critical to the formulation of sound land-use practices and building ordinances that may be implemented to minimize the danger of future fault movement.

Faults are numerous in the Helena area, but active faults—those that display evidence of movement in Holocene time (last 10,000 years)—have not been recognized. However, several faults in the area are categorized as potentially active fractures. They are confined to the Lewis and Clark line (figs. 3, 10), which appears to be the principal regional tectonic element in this part of Montana currently undergoing deformation. The crustal blocks north and south of the line, in the Helena area, are judged to be comparatively stable, and faults within those masses are believed to be inactive.

POTENTIALLY ACTIVE FAULTS

Six faults in the area are considered to be potentially active and likely to sustain future movement. They are the Bald Butte, Helena Valley, Scratchgravel Hills, Spokane Bench, Regulating Reservoir, and Spokane Hills faults.

In most places, these faults are covered by soil, loose rock, and young surficial deposits; and little is known about their surface pattern, the subsidiary faulting associated with them, and the width of the zone of surface disturbance along them. Seismological data on the fractures are also sparse; only a few small earthquakes, whose epicenters were accurately determined in 1973 (Freidline and others, 1976), can be confidently related to specific faults. Accordingly, more detailed information on these faults must be obtained before any realistic estimate of their capability to produce earthquakes can be made or the nature of ground deformation that may be associated with them during future movement can be predicted.

The general characteristics of the potentially active faults have already been described. A summary of those data and a tentative evaluation of the earthquake-hazard potential of the faults based upon the limited information now available are given here.

The Bald Butte and Helena Valley faults are many tens of kilometers long, extend far into the Earth's crust, and are many millions of years old. The principal movement on them was strike-slip and perhaps amounted to several kilometers. Deformation of stream deposits and slope wash along their traces has not been recognized, and it is uncertain that surface movements have occurred on the fractures in Holocene time (last 10,000 years).

However, the near coincidence of some earthquake epicenters with the traces of these faults (fig. 10) suggests that the faults are active and, because of their large dimensions, potentially capable of producing future damaging earthquakes. Where the faults cross bedrock and can be examined, they consist of a main break bordered by a zone of small, branching subsidiary faults and subparallel fractures that extend as much as 50 m outward from the main line of rupture. If either of the two faults was to undergo sudden, large-scale surface breakage, as might occur in a powerful earthquake, the greatest displacement probably would occur in a narrow zone along the main break, but significant ground deformation also might take place along the auxiliary faults and fractures that border the main fault line. Accordingly, earthquake-triggered surface breakage along either fault, in bedrock, might be distributed over a zone as much as 100 m wide. The effect of sudden fault rupture on surficial deposits that cover the fault traces cannot be accurately predicted, but records of historic surface faulting (Bonilla, 1970, p. 58-59) indicate that much of the deformation, especially larger displacements, probably would be transmitted upward through the surficial materials to the ground surface.

The Scratchgravel Hills fault is a normal fault more than 12 km long. It has a maximum vertical displacement of about 300 m. Along the eastern front of the Scratchgravel Hills, the fault is marked by a high, steep scarp produced by the fault movement. The fault trace, which lies at the base of the scarp, is in most places covered by surficial deposits laid down in the Holocene Epoch (last 10,000 years), and the age of the fault is uncertain. However, the geologically youthful state of the scarp suggests that fault displacement probably took place in the Pleistocene Epoch, between 10,000 and 2 million years ago. Moreover, the proximity of the inferred trace of the fault to the epicenters of three small earthquakes recorded in 1973 (fig. 10) suggests that those shocks may have originated on the fracture. On the basis of these relations, the fault is regarded as a potentially active fracture, and its dimensions indicate that it may be capable of generating a future earthquake of destructive magnitude. Because the fault is poorly exposed, the extent of ground breakage that might result from sudden surface displacement on it is difficult to predict. It is possible, however, that deformation might occur within a zone many meters wide along the fault trace.

The Spokane Bench fault is a normal fault about 20 km long. It has a maximum vertical displacement of about 100 m and probably extends into the bedrock floor beneath Helena Valley. Upthrow of older stream and lake deposits along the fault has produced a prominent scarp along the west and south sides of Spokane Bench. Over much of its length, the fault trace is covered by stream deposits of Holocene age (last 10,000 years), and major movement on the fracture predates those materials. However, trenching investigations across the fault near the Helena Valley Regulating Reservoir by the U.S. Bureau of Reclamation and the U.S. Geological Survey (M.W. Reynolds, written commun., 1977) have shown that the fracture deforms deposits of probable Pleistocene age (10,000-2 million years ago). Accordingly, the fault is regarded as a potentially active break. The length and displacement of the fault suggest that it is capable of generating future earthquakes, possibly of destructive magnitude. The zone of surface disturbance along the Spokane Bench fault, as determined by trenching, is as much as 50 m wide (M.W. Reynolds, oral commun., 1977); ground displacement triggered by an earthquake might be distributed over this broad strip of land.

The Regulating Reservoir fault is a normal fault about 6 km long. It has a maximum vertical displacement of about 30 m. Because it may have originated simultaneously with the parallel-trending Spokane Bench fault in Pleistocene time (10,000-2 million years ago), it is categorized as a potentially active fracture. However, the moderate dimensions of the Regulating Reservoir fault suggest that it is incapable of producing a destructive earthquake.

The Spokane Hills fault is a normal fault more than 11 km long. It has a minimum vertical displacement of several hundred meters and probably extends downward several kilometers in the Earth's crust. Upthrow of bedrock on the northeast side of the fracture has produced a steep scarp along its midlength. Geologic relations indicate that major displacement on the fault took place not long prior to 20,000 years ago, and it is therefore classified as a potentially active break. A low-magnitude earthquake centered near the southern trace of the fault in 1973 (fig. 10) might have originated on the rupture, and small earthquakes probably will occur on the fault in the future. Whether the Spokane Hills fault is capable of producing a destructive earthquake is problematical, but the dimensions of the fracture suggest that it may have such a potential. The main fault break is straight and narrow, is only a meter or two wide, and is accompanied by little subsidiary fracturing in the adjoining rocks. Sudden surface displacement, however, might be distributed over a fairly wide zone along the fault trace.

FAULTS PRONE TO REACTIVATION

In the area of major shaking of powerful earthquakes, faults other than the causative fracture may undergo sudden reactivation and produce large surface displacement (Bonilla, 1970, p. 55, fig. 3.5). A classic example of this phenomenon was the reactivation of four normal faults northeast of Hebgen Lake during the Montana earthquake of 1959, which produced scarps as much as 6 m high in the land surface (Witkind, 1964b, p. 37). Fault reactivation of this sort is most likely to occur on active faults, but large dormant faults also have undergone surface movement in strong earthquakes (Bonilla, 1970, p. 68).

The faults in the Helena area that are most susceptible to reactivation are the potentially active fractures within the Lewis and Clark line; namely, the Bald Butte, Helena Valley, Scratchgravel Hills, Spokane Bench, Regulating Reservoir, and Spokane Hills faults. The Silver Creek and Northwest valley faults and the concealed fault in the vicinity of Lake Helena (pl. 2), which appear to be dormant fractures within the Lewis and Clark line, also may be capable of rejuvenation. Although geologic criteria indicate that the normal faults in the crustal block south of the Lewis and Clark line are inactive, some of these fractures, especially the larger ones, may have the potential to reactivate when subjected to intense earthquake ground motion. Faults that are particularly suspect in this regard include the fractures at Willit Ridge, the fractures on either side of Mount Ascension that extend into the eastern section of Helena, and the large, north-trending fracture that ends against the Bald Butte fault about a kilometer southeast of Helena. The thrust faults in the Helena area, which lie in the crustal block north of the Lewis and Clark line (pl. 2), are very ancient; they are probably firmly healed and are unlikely to reactivate.

CONDITIONS CONDUCIVE TO REGIONAL GROUND DISPLACEMENT

In addition to ground displacement along the trace of faults, surface faulting also may produce regional warping or tilting of broad areas of the land surface. These regional distortions, when they occur suddenly, can have an enormous effect on surface waters; commonly they produce rapid water movements, permanent changes in water level, or changes in drainage pattern that result in widespread damage. A potential for regional ground displacement in the Helena area is provided by the Helena Valley, Spokane Bench, and Spokane Hills faults. Conceivably, movements of a few meters along these fractures could cause warping or tilting of broad areas of land in Helena Valley.

HYDROLOGIC CONDITIONS

Large earthquakes can generate destructive seiches and wave surges in rivers, lakes, and reservoirs and in industrial tanks by strong ground shaking or by regional displacement of the land surface. The potential magnitude of these effects is described in the section on "Seiches and surges." The principal bodies of water in the Helena area that are potentially susceptible to these hazards are Hauser Lake on the Missouri River, Lake Helena, and the Helena Valley Regulating Reservoir. The narrow portions of Hauser Lake north and south of Lakeside and in the lower canyon of Prickly Pear Creek, which would tend to constrict the oscillation of lake waters, might incur the greatest wave heights from seiching or surging. Other bodies of water in which earthquake-induced seiche effects might occur include Lake Stanchfield, the Northern Pacific Reservoir on McClellan Creek, the Hardie and Gehring Reservoirs on Threemile Creek, and the settling basin on Tenmile Creek. Damaging motions also might be produced in water-storage reservoirs and towers and in fuel-storage tanks in the area during a strong earthquake.

LAND USE AND EARTHQUAKE PROTECTION

GENERAL REMARKS

Economic losses and casualties from earthquakes in populated areas mainly result from ground-vibration damage to manmade structures. Accordingly, protection against earthquakes largely rests upon the engineering practice of making structures earthquake resistive. A brief commentary on earthquake-resistant design, directing attention to the seismic requirements in the Uniform Building Code and to earthquake engineering in general, is included in the appendix to this report.

Lately, much thought also has been focused on the possible effectiveness of land use as a supplement to engineering design in providing protection from earthquakes—land use in this context being broadly defined as the siting of vulnerable structures and concentrations of people away from the places where the potential danger from earthquake hazards is greatest. Conceivably, informed land use, if implemented over a long period of time, could be a very effective means for preventing structural damage, saving lives, and minimizing social disruption during earthquakes. Its application is particularly important in areas of rising population and rapid urban growth.

Land-use practice to counter earthquake effects must, of course, be undertaken judiciously. The proper goal is to establish a balance between the uses of land that satisfy the economic and functional needs of people and the uses that may provide appropriate public protection. Arbitrary land-use requirements that might unnecessarily discourage development should be avoided.

Geologic conditions in the Helena area that may moderate or enhance seismic hazards have been described in the section on "Local geologic conditions that may contribute to seismic hazards." A review of those conditions and of their possible implications for land use and earthquake protection is presented in the following discussion.

MODERATED MOTION ON BEDROCK

In destructive earthquakes, the intensity of ground shaking can vary substantially depending on the type of rock or soil that underlies the ground surface. Probably the most important relation in this regard, insofar as earthquake safety is concerned, is the fact that damage, and thus presumably the intensity and duration of shaking, is ordinarily less on solid bedrock or on other types of firm ground than on unconsolidated surficial deposits. A rudimentary analysis of the expected response of local rock units in future earthquakes, given in the section on "Expected response to ground shaking in future earthquakes," indicates somewhat more precisely that the intensity of ground motion on bedrock may be one or two and, in some instances, as much as three Mercalli-scale increments less than the intensity on surficial materials. This estimate generally agrees with data accumulated at earthquake sites in other parts of the world and with experimental results that show a marked lessening of ground-motion amplitude on bedrock. Accordingly, a large measure of protection from earthquake ground shaking may be realized by siting structures on or anchoring them to bedrock or other firm ground.

The ideal land-use practice to protect against earthquake ground shaking probably would be to locate all new structures on bedrock sites that are not susceptible to landslide, fault, or flood hazards, but such a procedure is usually impractical. For example, in the Helena area, most of the bedrock terrain is steep and mountainous and does not easily lend itself to large-scale development, so that urban growth is mainly directed onto the flat alluvial floor of Helena Valley where construction and orderly planning are easier and where water is plentiful. Nevertheless, the potential for saving lives and property merits that serious consideration be given to building on solid ground. This is particularly true for vital facilities such as hospitals, fire and police departments, rescue-squad facilities, powerplants, and communication centers as well as for high-occupancy structures such as schools, civic centers, theatres, office and apartment buildings, and large manufactories.

A sizable area of bedrock terrain suitable for urban development is located immediately east of Helena, mainly in secs. 27 and 34, but including portions of secs. 26, 28, 33, and 35 of T. 9 N., R. 3 W. Smaller areas of bedrock and of thinly covered bedrock near Helena, which are suited for some large-scale building purposes, are present west of Fort Harrison and on the south slope of the Scratchgravel Hills. Outlying areas of larger extent in which bedrock is at or near the ground surface, and in which the topography is generally favorable for construction, are located near Birdseye, south of Gearing (Gehring) station on Silver Creek, in the northwestern part of Helena Valley, and southeast of Montana City.

Steep bedrock terrain at the southern margin of Helena and in the mountains to the south, as well as hilly bedrock terrain in other areas, is mainly suited for home construction. However, care must be taken in those areas, especially if dense development is planned, to protect against earthquake-induced landsliding.

INTENSIFIED MOTION ON SURFICIAL DEPOSITS

Data presented in the section on "Expected response to ground shaking in future earthquakes" show that a general enhancement of ground motion may take place on surficial deposits relative to bedrock, that significant variations in the intensity of shaking may occur on different types of surficial materials, and that shaking may be intensified on water-saturated sediments in future strong earthquakes. In addition, the amplification of long-period motion in thick accumulations of older stream and lake deposits in Helena Valley may constitute a potential hazard. In general, protection against earthquake ground shaking on surficial deposits probably can be achieved through an appropriate combination of land-use and design measures.

RELATIVE INTENSITY ON SURFICIAL UNITS

Among the surficial units, it is expected that the intensity of ground shaking generally will be greatest on artificial fill, placer tailings, and landslide deposits; intermediate on stream deposits, slope wash, wind-laid deposits, glacial-lake deposits, older gravel, and older bentonitic clays; and least on the bulk of the older stream and lake deposits.

The intensity of ground motion on artificial fill, placer tailings, and landslide deposits might be as much as three Mercalli-scale increments higher than the overall intensity on bedrock in a future strong earthquake. Furthermore, these surficial units are highly prone to settlement, cracking, and slumping during earthquakes. Artificial fill, placer tailings, and landslide deposits therefore constitute some of the most seismically dangerous ground for building sites. The landslide deposits shown on plates 1 and 2 generally can be disregarded as a seismic risk, however, for they are in mountainous terrain far from populated areas.

In the urbanized parts of the Helena area, masses of artificial fill and placer tailings that may pose a substantial seismic risk to development include: (1) the large body of placer tailings that covers about 170 ha (400 acres) of land north and south of Custer Avenue, (2) the mass of artificial fill that covers about 20 ha (50 acres) of land along the lower part of Last Chance Gulch north of Neill Avenue, and (3) the stream deposits that underlie about 25 ha (60 acres) of land in the bottom of Last Chance Gulch, which were extensively worked for gold in earlier days and essentially constitute made land. The distribution of these materials is shown on plates 1 and 3. The severe structural damage that occurred in the upper part of Last Chance Gulch during the earthquake of 1935 (pl. 3) was attributed mainly to intensified shaking on the made ground, although differential settlement of the land may have played a part in some of the structural failure. This area was the site of extensive urban renewal in the 1970's including construction of several large, high-occupancy brick- and concrete-walled buildings.

Careful consideration should be given to future use of the land underlain by artificial fill and placer tailings. Before new structures are built on these deposits, the engineering and seismic characteristics of the materials should be thoroughly investigated to determine their potential dynamic response in future strong earthquakes, and appropriate design requirements should then be followed to effect proper protection against lateral earthquake forces and ground settlement. Low-density development, entailing use of the land for parks, golf courses, recreation areas, parking lots, and the like, would pose the least risk to loss of life and property from a destructive earthquake. Serious thought should also be given to a review of the design of newly built, high-occupancy structures sited on made land in Last Chance Gulch and on placer tailings along Custer Avenue to ensure that they meet building-code requirements for earthquake-resistant construction.

The intensity of ground shaking on stream deposits, slope wash, wind-laid deposits, glacial-lake deposits, older gravel, and older bentonitic clays is expected to be as much as two Mercalli increments higher than the intensity on bedrock in future strong earthquakes. Some of these surficial units also have a high susceptibility to ground failure, which increases the risk of building on them. Appropriate engineering investigations should therefore be made to evaluate the increased risk to structures sited on these materials. In general, protection from earthquake shaking on these deposits probably can be gained by a suitable combination of design requirements and land use. Urban development in the Helena area now is concentrated in the western part of Helena Valley on land underlain by stream deposits and slope wash.

The older stream and lake deposits (apart from bentonitic clays in the unit) constitute the firmest ground among the surficial materials, and the intensity of shaking on them in a strong earthquake ordinarily is expected to be no more than one Mercalli increment higher than the intensity on bedrock. Ground failure is also unlikely to occur on these materials. Accordingly, the bulk of the older stream and lake deposits generally present a lower seismic risk to structures and are from a seismic viewpoint more suited for high-density development than the other surficial units. A large area of older stream and lake deposits, covered in places by a thin veneer of older gravel, lies west and southwest of East Helena and extends to the vicinity of Montana City. Most of the eastern part of Helena Valley also is underlain by older stream and lake deposits (pl. 2).

WATER-SATURATED GROUND

A significant increase in the intensity of ground shaking may occur on unconsolidated surficial deposits in which the water table is near the ground surface. Medvedev (1965, p. 49) estimated that the intensity may increase one whole unit on the GOST intensity scale when the water table is within 1 m of the surface, and Gutenberg (1957, p. 235) determined that shaking may be greatly prolonged on water-saturated alluvial ground. Water-saturated sediments also are prone to earthquake-induced liquefaction, differential settlement, and cracking, which increase the seismic risk to structures built on those deposits.

The largest area of shallow water saturation in the Helena region is on stream deposits in the western part of Helena Valley, mainly to the south of Lake Helena. This area, which is generally outlined by the 6- and 12-ft (1.8- and 3.6-m) lines of equal water-table depth shown on plates 1 and 2, covers about 90 km^2 of the land surface. During the period of summer irrigation in the valley (June-September), the water table within much of the area bounded by the 6-ft (1.8-m) depth line reaches the surface and the ground is waterlogged, although drainage canals dug in the 1970's have partly alleviated this condition. Other areas underlain by surficial deposits in which the water table is close to the surface are present along the shores of Hauser Lake on the Missouri River and adjacent to the Helena Valley Regulating Reservoir in the eastern part of the area (pl. 2). These areas are relatively small.

Although most of the shallow-water-table land in Helena Valley is now in agricultural use and is thinly populated, significant urban development on the land has occurred locally and probably will continue in the future. Careful consideration should therefore be given to the practical steps that might be taken to reduce the increased risk of building on this ground. Before any comprehensive land-use program is devised for the area, however, the boundaries of the water-saturated land should be more precisely defined and engineering data should be obtained to accurately assess the potential performance of the ground in future strong earthquakes. When that information is available, appropriate design and land-use requirements can be formulated and implemented to effect seismic safety.

LONG-PERIOD MOTION IN HELENA VALLEY

In strong earthquakes, surface ground vibrations of long period (1.0-2.5 s) can be greatly amplified on thick accumulations of soft, loosely consolidated sediments that underlie broad alluvial valleys and basins. This amplification, which occurs at a frequency near the natural frequency of the deposits, causes the material to behave more or less like a shaken bowl of jelly during an earthquake. Shaking of this sort, which may be produced by shocks that originate far from the earthquake source, is potentially hazardous to high-rise buildings whose fundamental period of vibration roughly coincides with that of the ground. Severe long-period shaking occurred on lake beds that underlie Mexico City during strong earthquakes in 1957, 1962, and 1978 and caused extensive damage to tall buildings in the downtown area. Those earthquakes were centered more than 200 km from the city.

Helena Valley is underlain by a thick accumulation of older stream and lake deposits of Tertiary age. These deposits, which are physically similar to the lake beds beneath Mexico City, may have the potential to amplify long-period ground vibrations in future earthquakes. Accordingly, the potential earthquake performance of the older stream and lake sediments should be thoroughly investigated before high-rise structures are built on the valley floor. Dynamic analysis of individual sites and structures probably will be necessary to ensure the adequacy of the design of tall structures in the valley-floor area.

GROUND FAILURE ON SURFICIAL DEPOSITS

Surficial deposits commonly fail by landsliding, liquefaction, settlement, and cracking during earthquakes, and such failure usually becomes more prevalent as earthquake magnitude increases.

Surficial materials in the Helena area that may be highly susceptible to earthquake-triggered landsliding are present on steep hill and valley slopes; in streambank, lakeshore, and terrace scarps; and in steep-sided manmade embankments and excavations. Scarps and slopes with grades ranging from 60 percent to vertical have the greatest landslide potential, and structures should be sited a safe distance from these steeply inclined landforms unless the hazard can be overcome by site preparation or engineering design. Slopes with grades between 15 and 60 percent generally have less landslide risk, but locally they also may be highly unstable, especially if saturated with water, and their engineering characteristics and stability should be investigated prior to development. Slopes below 15-percent grade generally should have a low landslide potential under the prevailing dry climate, but liquefaction-induced slides might be triggered on these slopes by an earthquake if the slope materials are saturated with water, as might be the case during spring months or during periods of abnormally high rainfall.

Liquefaction, which may produce lateral movement, settlement, cracking, and flooding of ground, is likely to occur in water-saturated sands and silts in the stream deposits that underlie the western part of Helena Valley and in glacial-lake and other surficial units along the shores of Hauser Lake. Water-saturated flood-plain deposits along the major streams and water-saturated artificial fill and placer tailings also may be highly susceptible to liquefaction processes. The high potential for liquefaction-induced failure in these deposits, coupled with the possibility that ground shaking may be significantly intensified on them, greatly increases the seismic risk to structures sited on the water-saturated materials. The dynamic properties and liquefaction potential of these sediments therefore should be carefully evaluated prior to extensive land development. Methods for determining the degree of liquefaction to be expected in unconsolidated surficial units during strong earthquakes are described by Seed and Idriss (1971) and by Youd and others (1975).

Settlement and cracking of surficial deposits can be expected in a future strong earthquake. Artificial fill and placer tailings, the most weakly compacted of the surficial materials, probably are most susceptible to this kind of dislocation, which adds to the risk of building on them. Stream deposits, slope wash, glacial-lake deposits, wind-laid deposits, older gravel, and older stream and lake deposits also may be prone to settlement and cracking locally. Features most likely to undergo cracking include artificial earth embankments, streambanks, lakeshore scarps, and terrace and bench margins. Structures generally should be sited away from those landforms to avoid the cracking hazard, although locally it may be possible to alleviate the danger by site preparation. Widespread settlement and cracking might occur on the broad area of stream deposits in the western part of Helena Valley during a strong earthquake, especially in the area of shallow water saturation. The precise locale and severity of settlement and cracking on this wide expanse of land are largely unpredictable, however, and protection against these hazards is difficult by means other than earthquake-resistant design.

LANDSLIDING ON STEEP BEDROCK SLOPES

In major earthquakes, landslides in the form of soil slides, debris slides, and rockfalls are common on steep slopes underlain by bedrock, and, in rare instances, strong shaking may trigger large avalanches of solid rock on slopes that are unstable or marginally stable. Slides of this sort that occurred in the steep bedrock terrain around Hebgen Lake in the Montana earthquake of 1959 extensively damaged forests and roads and caused 28 fatalities.

Bedrock slopes ranging from 60 percent to vertical are abundant in the mountainous terrain in the Helena area, and many of them are seismically unsafe and dangerous to structures built on them or sited near their base or crest. The bottoms of narrow, deep, steep-walled valleys and the base of high, steep cliffs are particularly hazardous as building sites because of their vulnerability to earthquake-triggered landslides. A thorough evaluation of the stability of valley slopes and cliff faces and the probability of landsliding at a particular site should be made before structural development is undertaken.

FAULT HAZARD ABATEMENT

Surface fault displacement, which might occur in the Helena area in a large earthquake, is most likely to take place along the potentially active Bald Butte, Helena Valley, Scratchgravel Hills, Spokane Bench, Regulating Reservoir, and Spokane Hills faults. Other faults in the area, which are classed as inactive, constitute a lesser hazard. Surface faulting is usually distributed over a small area compared to the broad expanses of land that are disturbed by other earthquake effects.

Land-use and construction measures undertaken to counter the hazard of surface faulting must contend with the entire zone of deformation along a fault as well as with the main trace of the fracture, and fault hazard abatement generally has involved the adoption of building easements and zoning ordinances along and within fracture zones where they are reasonably well located. Steinbrugge (1968, p. 11-20), in a consideration of earthquake hazards in the San Francisco Bay area of California, suggested that three areas of different risk might be established in and near fault zones to guide land-use and construction practice. From lowest to highest risk, these areas are: (1) outside the fault zone, (2) within the broad fault zone but away from traces of active fault slip, and (3) on the main fault trace and on the trace of other ruptures in the zone that exhibit evidence of recent movement. Building easement and setback provisions adopted in 1971 by the town of Portola Valley, California, to deal with development on or near active strands of the San Andreas fault are described by Mader and others (1972, p. 845-857). This town and the city of Fremont, California, were the first communities officially to recognize the potential earthquake hazard of faults and to institute measures to cope with the danger. Figure 12 shows a portion of the zoning map establishing the setback provisions along the San Andreas fault at Portola Valley.

Further field investigation is necessary to evaluate fault hazards in the Helena area properly. Data are lacking on the location of buried fault traces, the level of seismicity and of seismic risk associated with specific faults, the width of fault zones, and the distribution of branch and secondary faults along major fractures. When this information becomes available, the method of fault-hazard zoning adopted at Portola Valley, California, might be advantageously applied to the potentially active fractures in the Helena area.

SHORELINE FLOODING

Flooding along the shores of lakes and reservoirs in the area might result from seiches, wave surges, or permanent submergence of land during future strong earthquakes. However, these effects are largely unpredictable, and few measures can be taken to minimize them except to site structures—especially vital structures—away from the areas of potential flooding.

FUTURE ASSESSMENT OF SEISMIC HAZARDS

SEISMIC MICROZONATION AND THE NEED FOR QUANTITATIVE EARTH-SCIENCE DATA

The ideal objective in earthquake hazards assessment is to obtain information that accurately defines the level of earthquake effects that can be expected in any area during future earthquakes of specific magnitude and location. The acquisition of this information and its presentation in map form constitute the practice of seismic microzonation or microregionalization. Such maps, which show in quantitative terms the potentials for ground shaking, surface faulting, landsliding, liquefaction, settlement, cracking, and flooding in different geographic areas, can provide a meaningful evaluation of earthquake hazards that is directly applicable to engineering design and to the formulation of effective building codes and land-use policies for earthquake protection. Detailed microzonation maps, based mainly on intensity-increment techniques (Medvedev, 1965, p. 1-98), have been prepared for many years in the U.S.S.R., and extensive work on seismic zoning is underway in other countries, including the United States. An early microregionalization (microzonation) map of expected maximum earthquake intensities in the Los Angeles basin of California is shown in figure 13.

An extensive summary of microzonation research and methodology is given in the Proceedings of two International Conferences on Microzonation for Safer Construction Research and Application, the first held in Seattle, Washington, from October 30 to November 3, 1972, and the second held in San Francisco, California, from November 26 to December 1, 1978.

The earth-science information in this report provides a broad definition of the earthquake problem and a general evaluation of potential seismic hazards in the Helena area. However, the data are limited and do not furnish a proper basis for making the kind of quantitative estimates of earthquake effects that are necessary for comprehensive seismic zoning and engineering application.

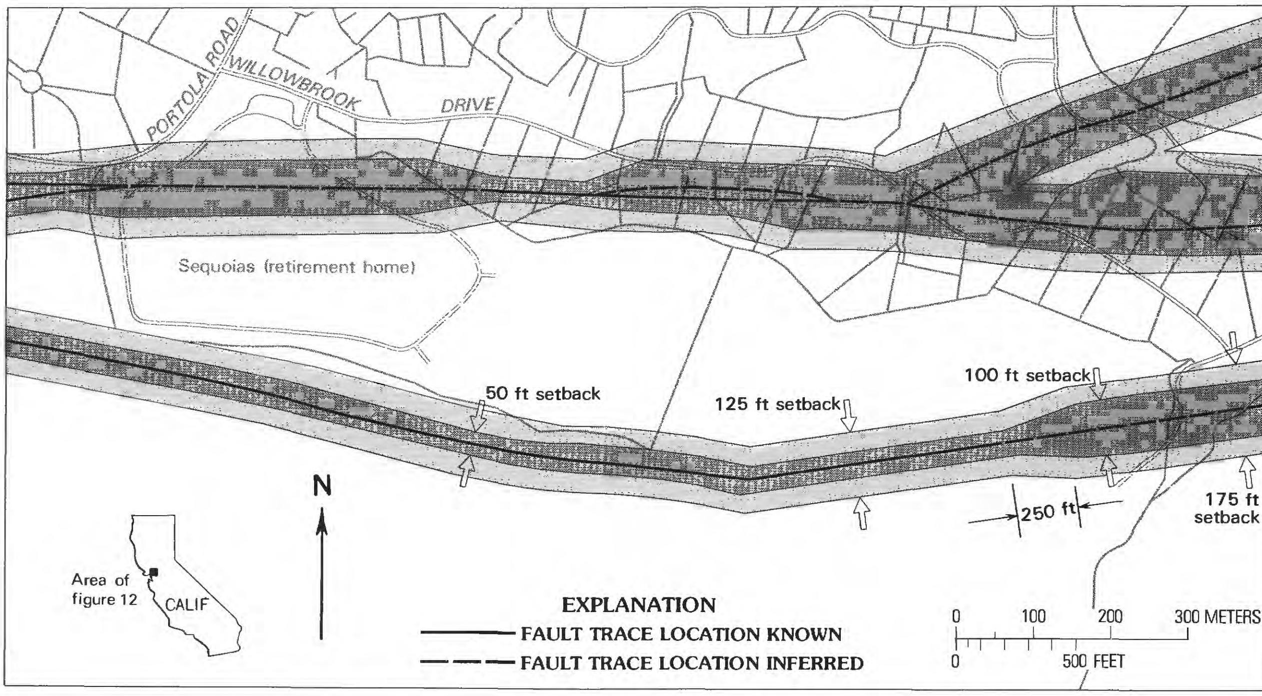


FIGURE 12.—Portion of zoning map establishing building setback requirements along strands of the San Andreas fault by town ordinance in Portola Valley, California. New building is prohibited within 50 ft (15 m) of the well-located trace of the fault (within area of dark shading), and structures with an occupancy larger than single-family homes must be sited 125 ft (38 m) from the fault trace (beyond area of light shading). On the inferred strand of the fault (dashed line), setbacks of 100 ft (30 m) are required for single-family dwellings and 175 ft (53 m) for structures of higher occupancy. From Mader and others (1972, fig. 5) as modified by Nichols and Buchanan-Banks (1974, fig. 10).

In particular, further studies are needed on regional and local seismicity, potential motions of local soils and surficial deposits under conditions of earthquake loading, physical characteristics of active faults and the microseismic activity associated with them, liquefaction potential of water-saturated sediments, stability of slopes in urban areas, and flood potential along lakes and reservoirs. Only by broadening the earth-science information base in a very substantial way will it be possible to formulate rational land-use policies and reliable engineering criteria to minimize seismic hazards in the area effectively. Some worthwhile earth-science investigations that are likely to yield valuable data for future hazard assessment in the Helena area are the following:

1. Monitoring microearthquake and small-earthquake activity with portable seismographs to determine local seismicity (the level of earthquake activity) and to locate epicenters with respect to specific faults.
2. Recording and measuring ground motions generated on different surficial and bedrock units by small earthquakes, distant underground nuclear tests, or quarry blasts to determine relative response of the rocks at low-strain levels and to delineate those geologic units on which ground shaking is likely to be least, intermediate, and greatest at sites equidistant from an earthquake source.
3. Determining shear-wave (*S*-wave) velocity in different types of bedrock and surficial deposits. The studies of Borcherdt and others (1979) indicate that measurements of *S*-wave velocity are a promising means for determining seismic-intensity increments in rock units. Evaluating this parameter as a means for zoning potential ground-motion intensity.
4. Determining basic engineering properties (such as density, porosity, shearing resistance, and stiffness) and layering and grain-size characteristics of surficial units to estimate their potential for ground failure from earthquake forces.
5. Measuring the thickness of surficial deposits above bedrock (depth to bedrock) which, along with *S*-wave velocity, can be used to determine the fundamental period of vibration of the materials in different geographical areas. The fundamental vibration frequency of the surficial units must be known to properly evaluate the problem of site-structure resonance in earthquake-engineering design.
6. Trenching across the trace of active faults at selected localities to determine the width of fault zones, the age

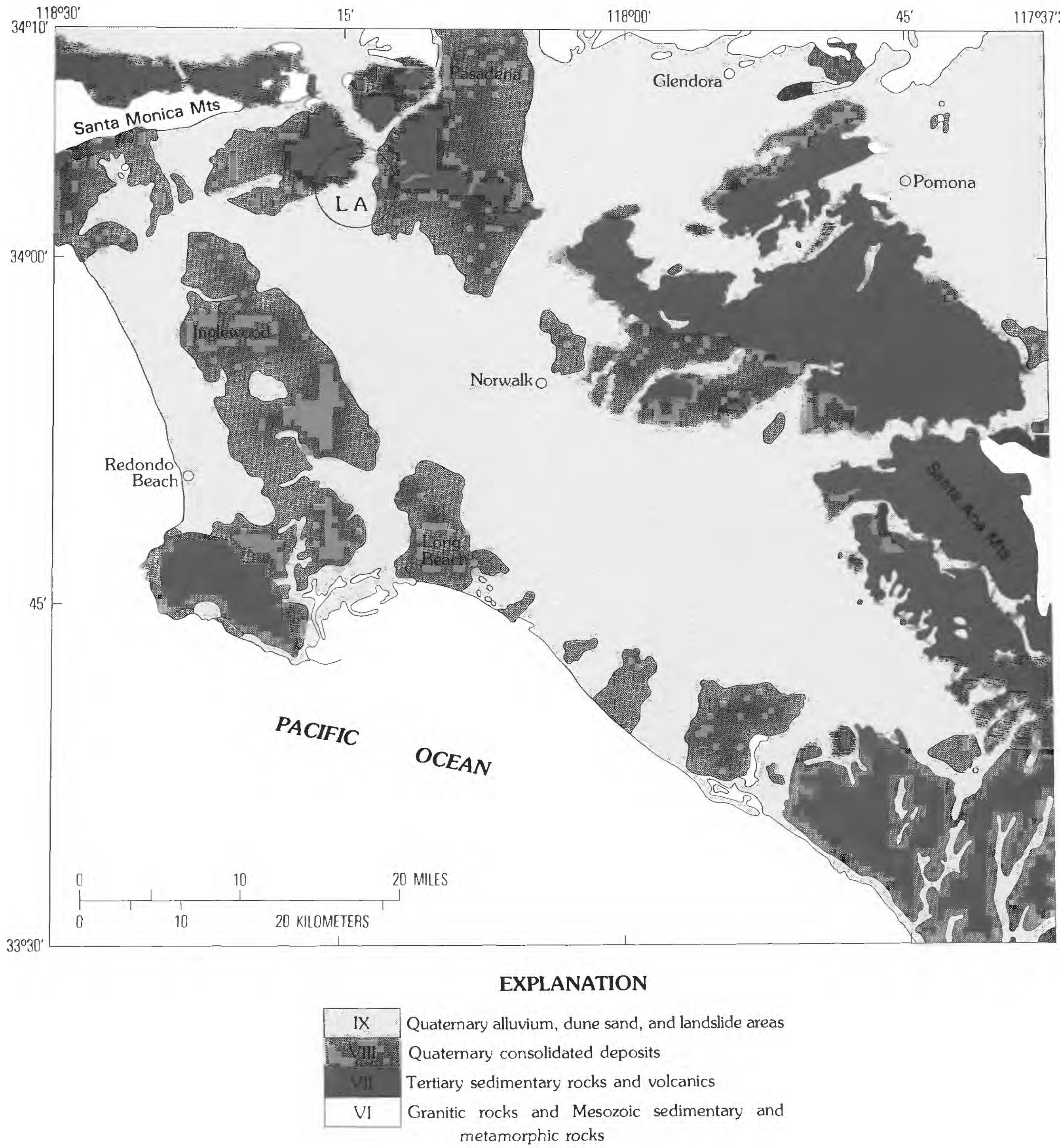


FIGURE 13.—Early microregionalization (microzonation) map of the Los Angeles basin and vicinity, California, showing expectable maximum Modified Mercalli intensity and prevailing geologic character of the ground. From Richter (1959, fig. 2) as modified by Barosh (1969, fig. 30).

and frequency of past fault movement, the type of fault displacement (normal, reverse or thrust, strike slip), and the nature of branch and secondary fractures.

7. Drilling to determine precise depths to water table and to accurately locate boundaries of areas of shallow water saturation in surficial materials in Helena Valley

and along the shores of Hauser Lake. Coincidental examination of the sediments in drill holes and laboratory determination of the physical properties of water-saturated sediment samples to evaluate liquefaction potential.

8. Geologic mapping in urban areas at large scale, coupled with limited drilling, to accurately locate boundaries between different surficial units and between surficial units and bedrock.
9. Determining the stability of slopes in urban areas to evaluate their potential for landsliding.
10. Investigating the topographic setting, depth, and shoreline and bottom configurations of Lake Helena, Hauser Lake, and the Helena Valley Regulating Reservoir to evaluate the flooding potential posed by earthquake-induced water waves.

ROLE OF THE U.S. GEOLOGICAL SURVEY

Seismological research in the U.S. Geological Survey is presently centered in a large program of work on earthquake hazards reduction in accordance with the provisions of the Earthquake Hazards Reduction Act of 1977 (U.S. Public Law 95-124). Regional studies on seismic hazards mitigation under this program are mainly concentrated in and near San Diego, Los Angeles, San Francisco, Seattle, Salt Lake City, St. Louis, Memphis, Charleston (S.C.), and Boston. Summaries of the research effort sponsored by the Earthquake Hazards Reduction Program of the U.S. Geological Survey have been presented by Hamilton (1978) and by Hays (1979). Some of the studies within this program will have broad application to the Helena area.

STATE AND LOCAL INVOLVEMENT

As the population of the Helena area increases, the earthquake hazard in the region becomes greater and greater. It is therefore important that some form of overall plan be devised to provide adequate protection to the public against future damaging earthquakes. Because of the diversity and complexity of earthquake effects, protection from them is difficult to achieve, and an effective program to reduce earthquake hazards requires a major, long-term effort that enlists the expertise and skills of many individuals from a variety of professions. The responsibility for planning and administering such a program in Montana will largely rest with the State Earthquake Hazard Mitigation Committee. Much of the research required for earthquake hazards assessment under the aegis of the committee could be accomplished by State and local agencies, colleges, and universities. The scale of the research effort that is undertaken largely depends upon funding; it may be appropriate for the State of Montana to provide continuing support to this important endeavor in future years.

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APPENDIX

MODIFIED MERCALLI INTENSITY SCALE OF 1931—ABRIDGED

(From Coffman and Cloud, 1970, p. 5, 7)

I. Not felt except by a very few under specially favorable circumstances.

II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motorcars may rock slightly. Vibration like passing truck. Duration estimated.

IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing motorcars rocked noticeably.

V. Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.

VI. Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.

VII. Everybody runs outdoors. Damage *negligible* in buildings of good design and construction; *slight to moderate* in well-built ordinary structures; *considerable* in poorly built or badly designed structures. Some chimneys broken. Noticed by persons driving motorcars.

VIII. Damage *slight* in specially designed structures; *considerable* in ordinary substantial buildings, with partial collapse; *great* in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motorcars disturbed.

IX. Damage *considerable* in specially designed structures; well-designed frame structures thrown out of plumb; *great* in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with their foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.

XI. Few, if any (masonry), structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII. Damage *total.* Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

COMMENTARY ON EARTHQUAKE-RESISTANT DESIGN

The minimum earthquake resistance requirements for new buildings in the United States are generally specified by the Uniform Building Code or UBC (International Conference of Building Officials, 1976). The essential purpose of these requirements is to protect against serious damage from moderate ground motions and against collapse and possible injury and loss of life from strong ground shaking.

The UBC provisions for earthquake-resistant building design specify the use of coefficients for determining design forces. In practice, these coefficients are entered in the design base shear formula, which defines the total lateral force or shear acting on the base of a structure. Coefficients are normally employed in the formula to account for the seismicity of an area (as determined from a seismic zonation map in the UBC), the seismic response of a structure relating to its fundamental period of vibration (base shear seismic coefficient), and the inherent resistance of different types of structures to earthquake loading (ductility factor). Commonly, a coefficient is also applied to the formula to account for the importance of a structure—that is, whether it is an essential facility such as a hospital or fire station. Additional coefficients can be introduced in the base shear equation, if sufficient data are available, to account for factors such as the local level of seismicity and the variability of site conditions affecting resonance. Other earthquake provisions in the UBC prescribe specific design and construction practices to effect earthquake resistance in structures.

The Helena area is in the highest zone (zone 3) on the seismic zonation map in the UBC. The earthquake provisions prescribed for this zone should be rigorously followed in future development of the area, both within the city and within the urbanized parts of Lewis and Clark County, to ensure some measure of overall seismic safety in this rapidly expanding region. Serious consideration also should be given to upgrading the earthquake resistance of vital facilities and high-occupancy structures that do not meet code requirements.

Although the seismic-coefficient method of design is probably satisfactory for ordinary buildings, many types of structures require seismic design procedures that are beyond the scope of building code provisions. Structures such as high-rise buildings, powerplants, stacks, water towers, bridges, and dams, for example, may require special design criteria and dynamic analysis to ensure protection against earthquake forces. The sophisticated procedures involved in earthquake engineering design and in structural dynamic analysis, whereby the earthquake performance of structures is evaluated by theoretical modeling, are treated in texts such as those of Wiegel (1970), Newmark and Rosenblueth (1971), Okamoto (1973), and Dowrick (1977).

A useful, popular account of basic earthquake-resistant building techniques, dealing primarily with single-family dwellings, has been presented by Yanev (1974). Among the many practical recommendations in his book are procedures for strengthening wood frames and brick and masonry walls, for bracing mobile homes against lateral earthquake forces, and for constructing hillside homes to avoid failure by landslip.

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[Italic type indicates major entry]